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DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

BULLETIN 607

THE WILLOW CREEK DISTRICT ALASKA

BY

STEPHEN R. CAPPS

WASHINGTON
GOVERNMENT PRINTING OFFICE
1915

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PREFACE.

By Alfred H. Brooks.

The exploration of the Susitna Valley, a part of the United States Geological Survey's first year's plan of Alaska surveys, was made by George H. Eldridge [1] and Robert Muldrow in 1898.[1] Eldridge's report contained the first official confirmation of the occurrence of alluvial gold in the Susitna basin. Meanwhile the prospectors had been at work and in 1897 discovered the Willow Creek placers. It was not until 1906 that the Geological Survey was able to extend its work in this field. Reconnaissance mapping was then carried over the entire Willow Creek basin and the salient features of its geology were determined. Gold-bearing quartz was found in this district during the same year and lode developments followed. This led to a second examination of the district by the Survey in 1910. The results of this second examination gave proof of the occurrence of valuable lodes, and plans were consequently made for a detailed survey. Because of urgent demands for work in other parts of the Territory, this detailed survey had to be deferred until 1913. It was then completed in one season, and the results are set forth in this volume.

The Willow Creek gold district lies along the contact zone of a great series of granodiorite intrusives that form much of the Talkeetna Mountains. As has been repeatedly pointed out, a large part of the gold deposits of Alaska occur in such contact zones. This is the condition in southeastern Alaska and in the Fairbanks, Chandalar, Iditarod, and other inland districts. The geology of the Willow Creek district is therefore favorable to the occurrence of gold deposits. Were it not for the intense glaciation of this field it would probably yield rich placers. As it is, the preglacial gravels that are most likely to contain bonanza placers have been swept away by glacial ice. The placers now found are chiefly postglacial concentrations, which are not likely to be so rich as the older gravels. In the absence of such rich placers and under the primitive conditions of transportation that existed until very recently, there has been little to attract the prospector, and hence the region has not been so carefully examined for mineral deposits as its geologic features would justify.

[1] Eldridge, G. H., A reconnaissance in the Susitna basin and adjacent territory, Alaska: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, pp. 1-29, 1900.

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1794 Salvador Fidalgo, a Spanish navigator, had entered the inl and three of Cook's officers, George Dixon and Nathaniel Portlo in 1786 and George Vancouver in 1794, had returned to the scene their earlier explorations. All these men made additions to Cook earlier chart of the shore line, but no attempt was made to carry tl surveys inland. Vancouver, however, completed the exploration the upper ends of Turnagain and Knik arms and recognized their tr character but failed to discover the mouth of Susitna River. Tl Susitna basin remained unknown until 1834, when the Russia Vassili Malakoff ascended the river, but little geographic knowledg of permanent value was obtained by his expedition. Mining i Alaska dates back to the expedition of a Russian mining enginee P. P. Doroshin, in 1848.[1] Sent by the Russian American Co. t search for mineral deposits in Cook Inlet, he chose a locality o Kenai River, and during the summers of 1848 and 1850 he succeede in extracting a few ounces of placer gold, but his operations were no commercially successful and the project was abandoned. In 185 the Russian American Co. commenced to mine coal on Port Graham at a locality which had been mentioned by Portlock in 1786, an mining was continued until the territory was transferred to th United States. In 1860 Russian maps which showed the general courses of Susitna and Matanuska rivers were published, though whether the Russians had actually explored all the area represented on these maps or whether their information had been procured from natives is not known. With the purchase of Alaska from Russia by the United States in 1867 the Russian fur trade was taken over by Americans, but the inland country tributary to Cook Inlet still remained unknown. The discovery of gold on Turnagain Arm was the impetus which sent many men to prospecting and exploring this great unknown portion of Alaska, and although these pioneers made their way to all parts of the Susitna and Matanuska basins, no accurate maps or descriptions of the country were published. The first discovery of gold is said to have been made in 1888, near Hope, but it was not until 1894 and 1895 that vigorous prospecting in that vicinity was carried on. In 1895 G. F. Becker[2] visited several localities on Cook Inlet and studied the geology and mineral resources.

Systematic surveys of this portion of Alaska were begun in 1898, when the discovery of the richness of the Klondike gold fields had focused the attention of the civilized world upon this great region. In that year G. H. Eldridge[3] and Robert Muldrow, of the United States Geological Survey, ascended Susitna River and crossed the

[1] Petrof, Ivan, Population, resources, etc., of Alaska: Tenth Census U. S., vol. 8, p. 78, 1884.

[2] Becker, G. F., Reconnaissance of the gold fields of southern Alaska, with some notes on the general geology: U. S. Geol. Survey Eighteenth Ann. Rept., pt. 3, pp. 7-100, 1898.

[3] Eldridge, G. H., A reconnaissance in the Susitna basin and adjacent territory, Alaska, in 1898: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, pp. 1-29, 1900.

divide to the head of Nenana River, while J. E. Spurr[1] and W. S. Post, also of the Geological Survey, made their way up the Skwentna, across the Alaska Range, and down the Kuskokwim. During the same year W. C. Mendenhall,[2] while attached to a War Department expedition in charge of Capt. F. W. Glenn, had ascended Matanuska River to its head and crossed the broad basin to the northwest as far as Delta River. All these expeditions resulted in the publication of exploratory geologic and topographic maps of the routes traversed and were the beginnings of precise knowledge of this previously unknown country.

PREVIOUS GEOLOGIC WORK.

Although the expeditions of 1898 yielded valuable contributions to knowledge of the general geology of the area tributary to Cook Inlet, Mendenhall's report was the only one which in any close way touched the Willow Creek district. His route lay from Knik up the broad lowland bordered on the north by the Talkeetna Mountains and on the south by Knik Arm and Matanuska River, and although his map indicates a part of the Little Susitna Valley, he gained no information concerning the bedrock geology until he had passed to the east of this district. In 1902 A. H. Brooks[3] made a trip from Tyonek, on the west shore of Cook Inlet, up Skwentna River and along the northwest slope of the Alaska Range and mapped the geology along his route, but on this expedition he gained no knowledge of the east side of the Susitna basin. The next expedition to this vicinity was made in 1905, when G. C. Martin[4] spent about three weeks in a study of the coal of the lower Matanuska Valley. His geologic map included a portion of the Little Susitna basin. In 1906 T. G. Gerdine and R. H. Sargent carried a reconnaissance survey around the Talkeetna Mountains, and Sidney Paige and Adolph Knopf[5] mapped the geology of the area surveyed. Their geologic map covered the Willow Creek district, but the small scale of the map and the hasty manner in which the field work was necessarily done imposed sharp limitations upon the amount of detail that could be presented. Although Paige spent only a few days in the Willow Creek district, in that short time he succeeded in dividing the rocks into the three main groups which are still recognized.

In 1909 R. H. Sargent completed a topographic map of the lower Matanuska Valley on a scale of 1: 62,500, and in 1910 this map was used as a base for a detailed geologic investigation of the coal fields by

[1] Spurr, J. E., A reconnaissance in southwestern Alaska in 1898: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, pp. 31-264, 1900.

[2] Mendenhall, W. C., A reconnaissance from Resurrection Bay to Tanana River, Alaska: Idem, pp. 265-340.

[3] The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, p. 16, 1911.

[4] A reconnaissance of the Matanuska coal field, Alaska, in 1905: U. S. Geol. Survey Bull. 289, 1906.

[5] Geologic reconnaissance in the Matanuska and Talkeetna basins: U. S. Geol. Survey Bull. 327, 1907.

G. C. Martin and F. J. Katz.[1] Their geologic map overlaps the map which accompanies this report (Pl. III, in pocket) on the southeast corner. In the fall of 1910 F. J. Katz and Theodore Chapin, after having left the Matanuska coal field, made a four days' trip into the Willow Creek district. In his report on the geology and mineral resources of the area Katz [2] described the economic development which had taken place up to that time and made some corrections to the geologic map of Paige and Knopf. In that same year a sketch map of the Willow Creek mining district, showing the general location of the mining claims and something of the drainage and topography of the district, was published by D. H. Sleem.

PRESENT INVESTIGATION.

Placer gold was first discovered in the Willow Creek district in 1897, and placer mining and prospecting have been carried on there to some extent ever since. The first gold quartz lode was located in 1906, and the later discovery of other gold lodes and active mining on three groups of claims have caused gold-lode mining to completely overshadow the feeble placer-mining industry. The geologic work done in the Willow Creek district by Paige, Katz, and Chapin, though it contributed greatly to the knowledge of the area, was done hurriedly and did not permit either close tracing of geologic boundaries or careful study of the ore deposits. Since their visits there has been a considerable advance in mining, and prospecting has been carried on continuously. The steadily increasing production of gold has attracted growing attention to this camp, and a more detailed examination of the geology and mineral resources than had hitherto been made seemed desirable. Plans were made to carry on this investigation in 1912, but the delay in appropriation of funds by Congress until late in August made the expedition impracticable that year. In 1913 it was determined to carry the delayed plans into effect. Accordingly C. E. Giffin was detailed to make a topographic map of the district, to be published on a scale of 1 : 62,500, and the writer was assigned to the study of the geology and ore deposits. The two parties, one consisting of the topographer, an assistant, and two camp hands, provided with four pack animals, and the other comprising the geologist, a packer, and a cook, with four pack horses, landed at Knik on July 13, 1913. Field work was commenced immediately and was continued by the topographic party until August 28 and by the geologic party until September 9. In that time both the topography and the geology of an area of about 90 square miles were mapped and all the mines and important prospects were visited. In this report free use has been made of the work of earlier investigators,

[1] Geology and coal fields of the lower Matanuska Valley, Alaska: U. S. Geol. Survey Bull. 500, 1912.
[2] Reconnaissance of the Willow Creek gold region: U. S. Geol. Survey Bull. 480, pp. 139-152, 1911.

especially that of Martin and Katz,[1] who studied the adjoining portion of the Matanuska Valley, and of Katz,[2] who described a number of prospects about which little additional information could be obtained. Thin sections of the unmineralized rocks collected were examined by J. E. Pogue, and the determinations of minerals and the classification of the rocks are the result of his study. A preliminary report on the mineral resources of the Willow Creek district has already been published.[3]

The writer wishes to express his indebtedness to the many miners and prospectors of the district for the expenditures of time and effort which they so willingly made in giving information about the properties, in supplying statistics, and in conducting him to the many points of interest.

GEOGRAPHY.

TOPOGRAPHY.

The Willow Creek district comprises the southwest corner of the Talkeetna Mountains. It is bordered on the south by the rolling lake-dotted lowland which lies between Knik Arm and the mountains and on the west by the broad Susitna Valley. The accompanying map (Pl. II, in pocket) does not cover the western part of the area commonly included in this district, but it shows that portion in which valuable discoveries of minerals have been made. The district is limited on the east and north by the basins of Little Susitna River and Willow Creek and their headward tributaries.

The north edge of the lowlands which lie between Knik Arm and the mountains extends along the southern border of the area shown on Plate II. In this lowland there are few bedrock exposures, the surface being an uneven rolling plain sloping gradually upward toward the mountains on the north. The form of the surface is much the same as it was when it was left by the retreating glacier. The innumerable lakes that dot the lowland are in general longest in an east-west direction, parallel to the direction of flow of the glacier that came down Matanuska Valley. The Knik lowland is directly continuous on the west and northwest with the Susitna lowland, which it resembles in topography and in mode of origin. In that part of the lowland over which the southward-flowing Susitna glacier moved the lakes are longest from north to south. Little Susitna River flows along the south base of the mountains and parallel to them in a shallow valley. Most of the lowland, however, is poorly drained, and

[1] Martin, G. C., and Katz, F. J., Geology and coal fields of the lower Matanuska Valley, Alaska: U. S. Geol. Survey Bull. 500, 1912.

[2] Katz, F. J., A reconnaissance of the Willow Creek gold region: U. S. Geol. Survey Bull. 480, pp. 139-152, 1911.

[3] Capps, S. R., Gold lodes and placers of the Willow Creek district: U. S. Geol. Survey Bull. 592, pp. 245-272, 1914.

there are few well-defined stream courses. It is well covered by a dense growth of spruce and birch, and the ridges afford firm ground for travel in the summer. The meadows and flats around the lakes and the marshy depressions between the hills are very soft when thawed and are difficult to cross with horses. No valuable minerals have been found in the lowlands, and their chief value will lie in their agricultural possibilities and timber resources.

The Knik lowland ends abruptly along its northern border and gives place to the Talkeetna Mountains, which rise steeply from the rolling plain. The mountain front is sharp, the long buttressing spurs common at the outer margins of mountain ranges being lacking. The straight line of the mountain face is due, in part at least, to the erosive action of the Matanuska Glacier, which once covered the lowland to a depth that in places exceeded 2,000 feet. The west slope of the mountains, in the Susitna Valley, is much more gentle. A large area in the heart of the Talkeetna Mountains, though unsurveyed, is known to be of the same general character as the surrounding regions that have been mapped. Near the west and north edges of the mountain mass the elevations are moderate and the summits of the ridges are rounded and smooth. Farther within the range the mountains are higher and more rugged and the crests consist of sharp peaks and pinnacled ridges. The highest peaks rise above 8,000 feet, and nearly all the larger streams head in glaciers. Most of the range is drained by Susitna and Matanuska rivers and their tributaries, although a considerable portion of its eastern slope falls within the Copper River basin.

DRAINAGE.

All the drainage from the Willow Creek district eventually finds its way to Cook Inlet, a part by way of Willow Creek and Susitna River and the remainder through Little Susitna River. Willow Creek heads opposite Fishhook Creek, in the heart of this mining district, and after following a southwestward course for 3 miles turns nearly due west and continues in that direction to its junction with Susitna River, 28 miles above the mouth of that stream. In the portion of its basin shown on Plate II Willow Creek flows in a broad U-shaped glaciated valley. West of the area mapped the mountains become smoother and lower, and as the great Susitna Valley is approached the stream flows across a broad high glacial bench and then descends somewhat abruptly through a canyon from which it emerges upon the Susitna flats. The area of the Willow Creek basin in the region here discussed is about 37 square miles. Within this district Willow Creek receives a number of tributary streams from the south, all of which drain the north slope of Bald Mountain Ridge. The largest of these tributaries from west to east are Wet, Grubstake,

and Homestake creeks, and two unnamed streams. From the north Willow Creek is fed by Shorty and Craigie creeks. No glaciers exist in the basin of the main fork of Willow Creek shown on the map (Pl. II), and all the streams are clear. Near its head Willow Creek flows in a broad gently sloping valley, and the small stream has not reduced its bed noticeably below the valley floor. Two miles below its source, however, it begins to intrench itself and flows in a narrow though not very deep canyon over large bowlders as far west as the mouth of Craigie Creek. Below that point there is a gradually widening stream flat composed of moderate-sized stream gravels, which extends westward to the limits of the area here discussed. The tributaries from the south all head in glacial cirques and occupy hanging valleys. This is particularly true of Wet, Grubstake, and Homestake creeks, all of which have waterfalls or cascades at their lower ends, at the points where they join the Willow Creek valley, and also of Shorty and Craigie creeks, which enter from the north. Craigie Creek falls 400 feet within half a mile of its mouth, although its average gradient for the next 5 miles above is only 120 feet to the mile.

Little Susitna River is much the largest stream in the district, that portion of its basin shown on Plate II having an area of about 86 square miles. Its headward branches rise on the slopes of rugged mountains, the loftiest peaks of which reach elevations well over 6,000 feet. Several small glaciers occupy favorable positions, and the largest one, at the head of the river, discharges enough sediment to cloud the waters of the stream during periods of rapid melting. The other glaciers are all small and inactive, and the streams which drain them are comparatively clear. The mountainous portion of the river valley is shown on the accompanying map (Pl. II), and its course is in general a little west of south. For the upper 5 miles of its length the stream flows in the bottom of a broad valley, into which it has intrenched its channel but little. Below the first big bend terraces appear along the sides of the stream, showing that the river has lowered its bed below the bottom of the trough as left by the glacier. Below the mouth of Reed Creek the trench through the glacial deposits becomes gradually deeper toward the canyon. At the point where the river emerges from the mountains it flows through a narrow rock canyon, below which it bends to the west, flows along the base of the mountains, and after crossing the lowlands enters the north end of Cook Inlet. Between the mouth of Archangel Creek and the canyon the river bed is filled with large bowlders, the current is swift, and during most of the summer the stream can be forded at few places and only with difficulty. One wagon bridge and three footbridges span the stream in this stretch. The largest tributaries of Little Susitna River are Fishhook Creek and Archangel Creek.

Fishhook Creek heads opposite Willow Creek (Pl. V, *B*), flows in a southerly direction for 3 miles through a high valley, turns sharply to the east, and descends abruptly from its hanging valley to join the Little Susitna, falling 1,100 feet in a distance of 1½ miles. The whole valley is a broadly U-shaped glacial valley and is itself bordered by a number of hanging cirques. The steep gradient of the stream has enabled it to intrench itself into its valley floor well toward its head, the stream channel being cut for the most part through glacial deposits. This stream trench begins a short distance above the upper mill and attains its greatest depth at the junction of the Fishhook and Little Susitna valleys, where the stream flows in a steep-sided gorge cut 200 feet below the bordering benches of glacial till.

Archangel Creek and its large northern branch, Reed Creek, both occupy broad U-shaped valleys surrounded by high mountains and in their lower courses flow through channels cut into the glacial morainic material. In the cirques in which all their tributaries head the streams flow for the most part close to bedrock.

INFLUENCE OF ROCK TYPES UPON TOPOGRAPHY.

In the Willow Creek district, as in other mountainous areas which have been subjected at no very remote time to intense glaciation, the tendency of the glaciers was to reduce all the divides to sharp ridges and to carve the valleys into broad U-shaped troughs with sweeping curves, leaving the valleys free from interlocking spurs and any other irregularities, and this work has been done without respect to the character of the rocks over which the ice moved. The type of rock has, however, had a notable effect on the topographic form, especially on the minor details, and each of the major geologic divisions shown on Plate III (in pocket) has a characteristic topography which distinguishes it from the other rock groups. The northern part of this district is composed of rocks of granitic character, which have in many places (Pl. IV, *A*) been eroded into sharp peaks and ragged, serrate ridges. The shape of the individual pinnacles is determined by the direction and abundance of joint cracks, and a sharp crag may be a single massive block of rock, its faces formed by joint planes. The talus from these ridges consists of angular blocks, some of which are of great size (Pl. V, *A*). The schist also weathers to form rugged peaks (Pl. IV, *B*), which are, however, quite different in appearance from those in the granitic areas. Sawtoothed ridges are lacking, and on close examination, the projecting points are seen to be intricately broken by a multitude of cracks. The rock waste from the schist mountains is composed for the most part of small fragments and is in sharp contrast to that from the granitic mountains.

Mountains carved from the Tertiary arkoses and sandstones bear some resemblance to the granitic mountains. The ridges are in

A. PART OF THE SOUTHWEST VALLEY WALL OF ARCHANGEL CREEK.

Showing typical rugged topography of the quartz diorite mountains.

B. EASTERN PART OF BALD MOUNTAIN RIDGE.

A characteristic mountain crest carved from mica schist.

places rough and ragged, and the talus consists of very coarse blocks. The bedding of the sediments has, however, exerted an influence upon the topography, which can readily be distinguished from that of the granitic areas (Pl. VI, *A*).

West of a line running north through the mouth of Craigie Creek the mountain summits are smooth and rounded and contrast strongly with the sharp peaks and ridges of the higher mountains to the north and east. This lack of ruggedness is not due to the character of the rock, for it appears on mountains composed of granitic, schistose, and sedimentary rocks. The cause of this difference in topographic character is to be attributed to the lower altitude of the mountains on the west border of the Talkeetna Range and their consequent freedom from severe glacial erosion. In the higher mountains each small valley head once contained a glacier and each glacier excavated its bed to form a glacial cirque. The cutting of these cirques into the mountains from all sides has reduced the crests to sharp ridges and peaks. In the lower mountains the altitude was insufficient for local glaciers to maintain themselves, and although the main valleys were eroded by ice streams whose sources were in the higher parts of the range, the local glaciers were fewer and more feeble, and the cirques were more widely spaced, leaving considerable areas of the old upland surface unsculptured by glacial ice (Pl. IX, *B*). In the lowlands, both south and west of the mountains, the larger topographic features are probably due to the form of the underlying bedrock as left by the ice, although exposures of rock in place are rare, but the minor details of surface configuration are due to the action of the glacial ice on the surficial deposits, the region having in general the mild hummock and kettle topography of glacial moraines, somewhat modified locally by the cutting of postglacial stream valleys.

CLIMATE.

The Willow Creek district is, at its nearest point, only 10 miles from tidewater on Knik Arm, but the distance to the main line of the Pacific coast on the south is 120 miles, and high mountains lie between, so that the climate of the district more closely resembles that of interior Alaska than that of the coastal region. So far as is known, no systematic records of precipitation or temperature have been kept in the Susitna basin. It is well known, however, that the winters are longer and colder and the summers warmer than on the coastal belt, where the ocean waters have an equalizing effect on the temperature. The precipitation, though generally less than on the coast, is much heavier, both in summer and in winter, than it is north of the Alaska Range, the high mountains of the Talkeetna Range and of the Chugach Range south of Matanuska River having a noticeable

influence on the distribution of the precipitation. The amount rain and snow varies greatly in different years. In 1912, it is sa rain fell almost continuously during the summer. The summer 1913 is said to have been unusually dry; between July 13 and Se tember 17 it rained or snowed all day for only eight days and duri parts of five other days. In general, the Willow Creek district li within the area of moderate rainfall that includes much of the low Susitna basin.

Activities in any Alaskan mining camp are to a large exte determined by the season. In the winter, when the ground covered with snow and the streams are frozen, surface prospecti is abandoned, mining is confined to underground work, and mi which depend on water power are closed. The transportation supplies, however, is facilitated by the snow, and the streams a marshes, which are impassable in summer, offer good routes f sledding in the winter. In the summer surface mining, millin construction work, and prospecting are carried on. The length the open season is therefore an important factor in determining t mining costs in any camp. From the last of November to late April or early in May the ice in upper Cook Inlet prevents navigati to Knik Anchorage, and the streams in the Willow Creek district ar usually frozen and the ground snow covered. From late in Ma until late in October surface mining may be done, thus giving maximum working season of nearly 150 days, a somewhat longe period than is available in interior Alaska.

VEGETATION.

After the break-up in the spring, when the streams become free from ice and the snow first disappears from exposed slopes, the approach of summer is astonishingly rapid. Vegetation springs up as soon as the ground is bare of snow, and the long hours of sunlight and the warm days cause the snow to disappear quickly and the plants to grow with great rapidity and luxuriance. To those who use horses the appearance of grass for forage is an important event. Sufficient grass to support stock appears in the lowlands by the middle of May, and from that time until the heavy frosts late in September have withered it forage for horses is nearly everywhere abundant. The most common grass is of a variety known as red top, which is widely distributed in the timbered lowlands, among the alders and willows above timber line, and up the mountain slopes to an elevation of about 2,500 feet. It grows with remarkable luxuriance, in some places to a height of 6 or 7 feet (Pl. VI, *B*), and over thousands of acres its growth is so dense as to seriously retard progress through it. This grass makes good hay when properly cut and cured, but when withered frost in the fall it affords little nourishment for stock, and horses ked after that time must be fed on hay and grain. Bracken

ferns and the brilliant fire weed also grow among the red top, and in the fall the downy seeds of the fire weed may be seen drifting across the summits of the highest mountains.

The distribution of timber in the district is shown in figure 1. It will be seen that most of the mountainous region is destitute of timber, trees appearing only in the lowlands, on the lower slopes of the mountains, and in the larger valleys. In the lowlands there is

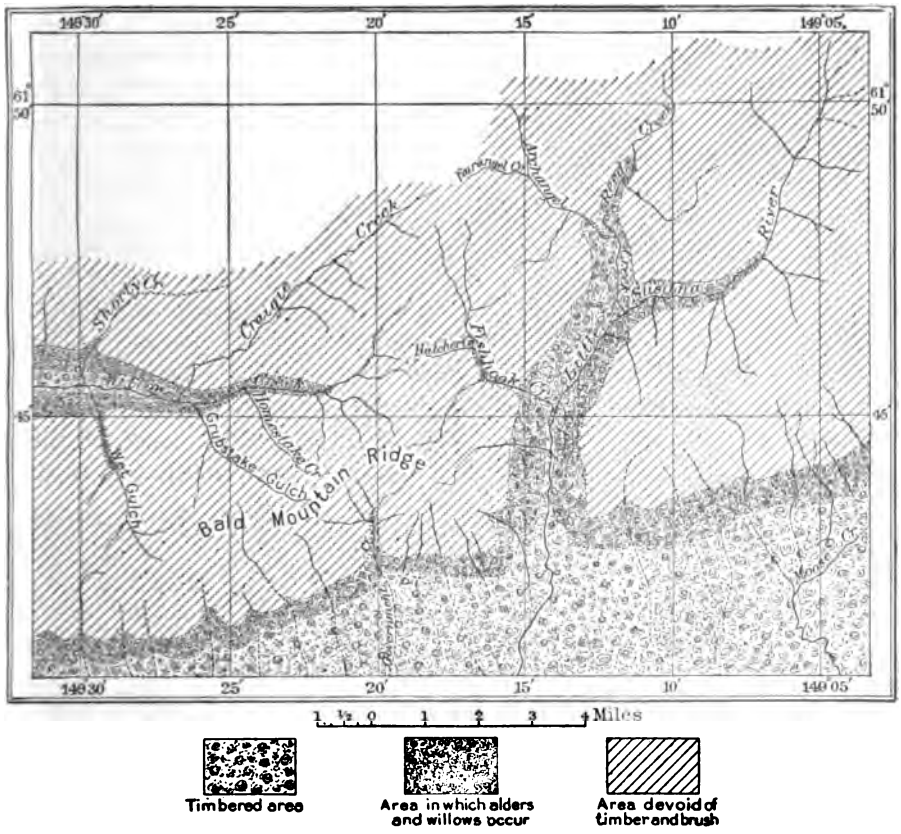

FIGURE 1.—Sketch map showing distribution of timber and brush in the Willow Creek district.

an abundant growth of spruce and birch, with cottonwood along the stream courses. Most of the birch trees do not exceed a foot in diameter, and this wood is used principally for fuel. Spruce trees with a diameter of 2 feet at the base are not uncommon and yield lumber of a very fair grade for buildings, sluice boxes, and mining purposes. Spruce is also preferred to birch for firewood in camps where the logs must be hauled some distance, as the wood makes good fuel and is much lighter than birch. Little use is made of the cottonwood, although the trees grow to greater size than either the spruce or the birch.

As timber line is approached, at an elevation of 1,500 to 2,000 feet, the trees become scattered and give way to a dense growth of alder bushes, in which travel is difficult and through which it is necessary to chop trails for horses. Alders grow in scattered clumps up to altitudes of 2,500 to 3,000 feet, and willow bushes extend to somewhat greater heights. For the prospector's camp fire alders are used almost exclusively, for they may be found at much greater altitudes than the more desirable spruce, but even alders must in many places be brought several miles. Alder wood can be burned green in a stove, and it soon dries out if cut and split and makes an excellent firewood.

In Little Susitna Valley some good spruce formerly grew as far north as the mouth of Fishhook Creek, but the demand for this wood has already caused the cutting of practically all the good trees above the canyon, and it is now necessary to haul logs about 7 miles to the mines on Fishhook Creek. Timber for the mine on Craigie Creek is obtained about 4 miles away, the upper limit of spruce on Willow Creek being at about the mouth of Craigie Creek.

Sphagnum mosses are widely distributed, especially among the timber in the lowlands. Above the altitude to which grass and ferns grow the slopes are covered by a thin growth of moss and heather, which in places shows a curious arrangement of hummocks or of ridges and furrows. (See Pl. VII, *A* and *B*.) The cause of this irregular surface is not definitely known, but it probably has to do with the action of alternate freezing and thawing.

POPULATION.

Knik village, on the northwest shore of Knik Arm, has long been a native settlement. For at least 15 years there has been a trading station at that place, and in 1910 the population was 118, including natives and whites. By 1913 the village had increased in white population and contained stores, road houses, a church, and a schoolhouse. It is the center of supplies for the Willow Creek district and the Matanuska Valley. The first white men to settle in the Willow Creek region were those who discovered placer gold on that stream in 1897, and this small placer camp contained the total population for several years. Since the first discovery of gold lodes in 1906 the mining population has steadily increased, and it is estimated that in 1913 there were about 100 people in the district. Of these, about 70 were engaged in mining and the rest in prospecting.

There are no permanent settlements of natives nearer than Knik. The Indians spend most of their time fishing and hunting near the shores of Knik Arm and in upper Cook Inlet, but in the fall and winter hunting and trapping trips are undertaken throughout the adjoining country.

A. INTERBEDDED ARKOSE AND SHALE BEDS AT THE HEAD OF DELIA CREEK.

B. LUXURIANT GROWTH OF RED-TOP GRASS NEAR THE CANYON OF LITTLE SUSITNA RIVER.

A. MOSS AND HEATHER RIDGES ON TOP OF BALD MOUNTAIN RIDGE.

B. MOSS AND HEATHER HUMMOCKS ON TOP OF BALD MOUNTAIN RIDGE.

SUPPLIES AND TRANSPORTATION.

The Willow Creek district is always approached by way of the village of Knik, which is the center of supplies for this region. Although Knik is situated on Knik Arm, an embayment of Cook Inlet, it is on the shallow upper portion of the inlet and can be reached by boat only at high tide. When the tide is out no water is visible from the village, which then looks out upon miles of barren mud flats cut by an irregular network of tidal channels. At high tide boats drawing several feet of water may reach the town by following one of the deeper channels. During about half the year the upper part of Cook Inlet is closed to navigation on account of the ice which forms in it. The head of the inlet is made brackish by the large quantity of fresh water which it receives from Susitna, Matanuska, and other rivers, and on this brackish water ice forms more readily than on the normal salt water. The mean tidal range is about 30 feet, and in the rapid currents formed by the tides the ice is carried back and forth and renders navigation impossible during the winter. During this time the village maintains communication with the coast by way of a trail which crosses the divide at the head of Crow Creek, passes around the head of Turnagain Arm, and thence follows the general course of the railroad to Seward. The mail is brought over this route by dog trains, but the other traffic is so small as to be negligible.

During the open season practically all travelers to Knik go by ocean steamer to Knik Anchorage, near the mouth of Ship Creek, about 18 miles below the town. From the anchorage freight is lightered by scows to Knik and passengers are transferred by launch. In 1913, between May and November, one steamship, plying from Seattle through southeastern Alaska to ports on the Gulf of Alaska and Cook Inlet, made trips every three weeks to Knik Anchorage. The passenger rate in 1913 between Seattle and Knik Anchorage was $55 each way. The freight rate varied with the class of material shipped but was $30 each for horses and from $15 to $26 a ton for groceries and provisions. Wharfage at Seattle was not included in these charges, and the additional cost of transportation from Knik Anchorage to Knik was $2 each for passengers, $8 a head for horses, and 30 to 40 per cent of the freight rate from Seattle to Knik Anchorage for supplies.

Two routes were formerly in general use between Knik and the mines in the Willow Creek district, both of which followed the shore of Knik Arm in a northeasterly direction as far as the mouth of Cottonwood Creek, 6 miles from Knik. From Cottonwood the Bald Mountain trail extends northward across the lowlands, crosses Bald Mountain Ridge into the head of Wet Gulch, follows Wet Gulch to its mouth, and thence goes up Willow Creek. One branch extends up Craigie Creek valley, and another crosses the divide to the Little

Susitna basin, follows down Hatcher Creek, and ends at the mines on upper Fishhook Creek. The portion of this trail which lies in the mountains affords good footing, but the stretch between Cottonwood and Bald Mountain Ridge is said to be soft in summer. The lowland portion is now little used. The other route was the old Carle wagon road, which extended from Cottonwood northeastward to Little Susitna River, several miles below the canyon, and after crossing that stream kept on its west side to Fishhook Creek, which it followed up to the mines. The Carle road has now been displaced by a new wagon road completed by the Alaska Road Commission in 1913. This road follows the general course of the Carle road from Knik for 23 miles, but keeps to the right of Little Susitna River as far as the canyon, crosses it in the canyon, and extends up the west bank of the stream and up Fishhook Creek to the mines. This road is well graded, is furnished with good bridges, and is now used for practically all summer travel to the Willow Creek district as well as for winter travel to points in the Fishhook and Little Susitna valleys. The winter road for sledding to the Willow Creek basin leads northward from Knik, skirts the west end of Bald Mountain Ridge, and proceeds up Willow Creek.

The summer freight rate by wagon to upper Fishhook Creek from Knik is from 4 to 5 cents a pound. Supplies for the Willow Creek basin must be transported by pack train from Fishhook Creek, at a considerable additional expense. In winter freight may be sledded to the camps by either the new wagon road or the Willow Creek winter road, at about half the cost of summer transportation. The district will be made readily accessible by the Government railroad from Seward to Fairbanks, construction of which has been begun. This railroad will pass close to the southern margin of the district, and the distance to Seward, its coastal terminal, will be about 165 miles.[1] The plan includes a branch line into the Matanuska coal field, with another tidewater terminal at the mouth of Ship Creek near the entrance to Knik Arm, which will be available during the season of open navigation on Cook Inlet.

GEOLOGY.

PRINCIPAL FEATURES.

The areal distribution of the geologic formations of the Willow Creek district is shown on the accompanying map (Pl. III, in pocket) and the relations of the various rock formations to one another are represented in a generalized form in figure 2. The details of distribution of the different formations as shown on the geologic map differ somewhat from those shown on earlier published maps of this district, more accurate representation having been made possible by

[1] Railway routes in Alaska: Alaska Railroad Comm. Rept., House Doc. No. 1346, pts. 1 and 2, 62d Cong., 3d sess., 1913.

the longer time available for the actual tracing of geologic boundaries and by the completion of a base map on a larger scale than those previously published. The Willow Creek district was only a small part of a large area that was under investigation during the earlier surveys, and only a short time could then be spent in it. Nevertheless, the main subdivisions made by Paige and Knopf [1] and later by

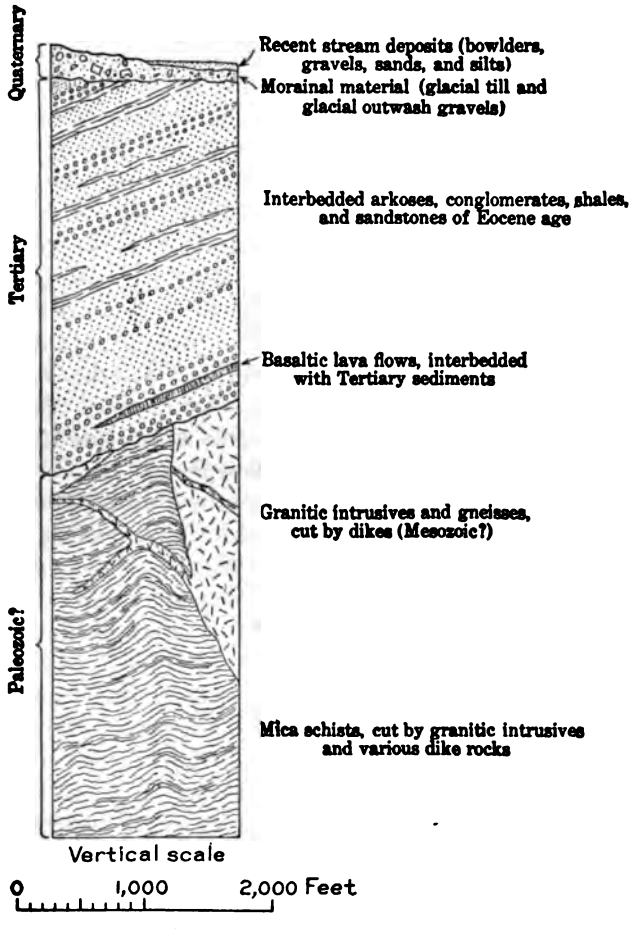

FIGURE 2.—Generalized columnar section of the rocks of the Willow Creek district.

Katz [2] are adopted here. The schists, most of which lie between Bald Mountain Ridge and Willow Creek, are the oldest rocks in the Willow Creek district and probably also in the entire Talkeetna Mountain region. They consist of highly fissile thoroughly foliated garnetiferous mica schists and chlorite-albite schists and are every-

[1] Paige, Sidney, and Knopf, Adolph, Geologic reconnaissance in the Matanuska and Talkeetna basins, Alaska: U. S. Geol. Survey Bull. 327, Pl. II, 1907.

[2] Katz, F. J., A reconnaissance of the Willow Creek gold region: U. S. Geol. Survey Bull. 480, p. 143, 1911.

where very uniform in appearance. On the north they are cut off by intrusive quartz diorite and on the south they are overlain in part by gneisses and in part by Tertiary sediments. The schists have been cut by dikes of various kinds, some of which have themselves been metamorphosed along with the rocks which they intrude. The numerous quartz veins in the schists are probably the source of a part of the placer gold of the district (see p. 27), but, although some of these veins are rather large, no encouraging lode prospects have been found in the schist area. The great alteration of the schists indicates that the rocks from which they were derived were subjected to intense metamorphism for a long time. Neither the original character of these rocks nor their age is known, but their antiquity may be shown by comparing them with the much less altered Mesozoic rocks of the lower Matanuska Valley. At any rate, a long time elapsed between the deposition of the rocks that formed the schists and the intrusion of the next younger rocks of this district, the quartz diorites. Granitic rocks of the same general type as the quartz diorite form a large part of the Talkeetna Mountain mass and extend southward toward its southern margin. Whether or not these rocks were all intruded at the same time is not known. Several separate intrusions may be represented in this area; but it is certain that the schists had been greatly metamorphosed before they were cut by the granitic rocks, which are therefore much younger than the schists. In many places in this district the granitic rocks are decidedly gneissic along their southern border, as if the edges of the intrusion had been somewhat metamorphosed, whereas the main granitic mass to the north has remained massive and unaltered. A gradation from massive quartz diorite to a banded, somewhat gneissic rock, was seen, so it was not practicable to draw a line separating the gneiss from the unaltered diorite. In its characteristic development, however, the gneiss is very different in appearance from the diorite, and it is possible that some of the gneisses are older than the unaltered quartz diorites that form the heart of the Talkeetna Range. If a part of the gneiss is older than the main quartz diorite intrusion, that fact would indicate another period of metamorphism later than that which altered the schists but earlier than the intrusion of the diorite, for the gneisses are less profoundly metamorphosed than the schists. On the other hand, if the gneisses include parts of the main quartz diorite intrusion, then there was local metamorphism along the southern border of that intrusion which affected the rocks at some places but did not extend far into the intruded mass.

During the intrusion of the granitic rocks many dikes, of similar composition to the main intrusive mass, were injected into the sur-

rounding rocks or into those parts of the intrusion itself, which cooled sufficiently to form cracks into which the dikes could penetrate. These dikes are, in general, light-colored fine-grained rocks, consisting, principally, of quartz and feldspar, and have been classified as aplite or alaskite dikes. After the intruded igneous rocks had cooled another long interval elapsed, during which erosion reduced the country to a surface of rather low relief and removed much material from the schist and quartz diorite areas. Upon this surface fresh-water deposits of Eocene age, consisting of muds, sands, coarse grits, and gravels, with abundant plant fragments and some coal, were laid down, sedimentation being interrupted in places by thin flows of basaltic lava. In adjacent areas the Eocene beds were succeeded conformably by conglomerates, which, after an erosion interval, were capped by lava flows and accumulations of volcanic breccias and tuffs; but if these materials were deposited in the Willow Creek district they were later removed by erosion, for no trace of them now remains. Next followed a period of uplift, during which the Eocene sediments, now hard rock, and any later deposits which may then have existed were tilted and gently folded. Upon this land mass streams carved their valleys and developed a rather mature though rugged topography. The next notable geologic event in this district was the accumulation of the great glaciers, which occupied all of the large valleys. The glaciers, by their erosion, profoundly altered the shapes of the basins and in their upper courses gathered an enormous load of soil and rock, which they transported for some distance and then dropped upon the surface of the older rock formations. The glacial deposits consist of morainal material dropped by the ice and of gravels supplied by the glaciers, but transported, rounded, and assorted, and then deposited by the glacial streams. The morainal deposits commonly consist of a clayey matrix through which pebbles, bowlders, and angular fragments of rock are scattered indiscriminately without assortment. Glacial striæ may be found on some of these fragments of rock, but the quartz diorite, of which most of them are composed, is hard and does not take striæ readily. Deposits of glacial outwash gravels are of minor amount in this district, the morainal deposits predominating. The glacial deposits shown on Plate III vary greatly in thickness from place to place, but over the area represented are of sufficient thickness to conceal the underlying hard-rock formations. The most recent deposits here considered are the gravels of the present streams, which form narrow strips along the bottoms of most of the stream valleys, but in general cover areas too small to be shown on a map of this scale.

SEDIMENTARY ROCKS.

MICA SCHIST.

DISTRIBUTION AND CHARACTER.

As has already been stated, the mica schists occupy an area which in large part lies north of the crest of Bald Mountain Ridge, west of Little Susitna Valley, and south of Willow Creek. (See Pl. III, in pocket.) These limits are only approximate, for in places the outcrops of the schist extend a short distance south of Bald Mountain Ridge, especially in the valley of Government Creek, and the schist itself underlies much of the Bald Mountain Ridge beneath a comparatively thin cover of gneiss and Tertiary beds. On the north the schist is found over half a mile north of Willow Creek in the Craigie Creek canyon, being cut off on its north edge by the quartz diorite intrusive mass. On the west it extends beyond the area of the present investigation but is known to disappear beneath the glacial deposits on the edge of Susitna Valley. On the whole, however, the schist area here outlined is an isolated occurrence, no other rocks of this type having been seen in the Talkeetna Mountains or the lower Susitna basin. The resemblance of these schists to schists in the interior of Alaska will be discussed in another part of this report.

The schists may be seen in excellent exposures in a great number of places, especially at the heads of the cirques which cut Bald Mountain Ridge on the north. (See Pl. IV, *B*.) The predominant rocks are highly contorted mica schists and phyllites, which readily cleave into thin flakes along the lines of schistosity. The weathered surface phases are so friable that firm hand specimens could be procured with difficulty. The cleavage planes are not smooth but have an irregular, knotty appearance as they curve around included particles of more resistant minerals. In color the schists range from whitish, silvery rocks through reddish and green phases, the unweathered rocks having in general a greenish, silvery cast, a reddish tinge appearing on weathered surfaces, probably due to the oxidation of iron-bearing minerals. In the fresh exposures of recent stream canyons the schist appears to be rather massive and breaks along joint planes into large, angular blocks. When weathered the rock separates along the lines of schistosity into thin flakes and slabs. (See Pl. VIII, *A*.) The degree of schistosity varies from place to place; in some outcrops the rock appears rather massive and free from well-developed cleavage; in others it shows a large percentage of mica and is very fissile. Included within the schists are certain massive lenses of basic rock which have locally been considerably sheared and metamorphosed. In Grubstake Gulch rocks which presumably came from the schist series had been altered to satiny,

A. CHARACTERISTIC WEATHERED SURFACE OF A BLOCK OF MICA SCHIST.

B. GLACIAL LATERAL MORAINES ACROSS THE MOUTH OF SIDNEY CREEK VALLEY.

light-green amphibole asbestos. The asbestos fibers are brittle and somewhat bent, and the material is probably of too low grade to be commercially valuable. Quartz veins are abundant in the schists and show a tendency to follow the schistose structure, although many cut across the schistosity. Veins 1 to 4 feet thick were seen, and some of these could be traced for several hundred feet along the surface. The quartz is characteristically massive, milk-white in color, and is remarkably free from mineralization. Even a small quantity of pyrite in this quartz would reveal itself by rusty stains on the weathered outcrops, yet such stains are infrequent. Many samples of the quartz that have been crushed and panned by prospectors yielded no free gold, and assays yield from a trace to about $1 per ton. Besides being cut by the large, conspicuous quartz veins, the schist is at many places intricately cut by tiny quartz veinlets, some no thicker than a sheet of paper. No assays have been made of the quartz of these veinlets, and its metallic content is not known. It seems certain, however, that much of the placer gold of Grubstake Gulch has been derived from the schist, and it is probably contained in the quartz veins and veinlets and concentrated from them into the valley bottom by erosion.

At different times the schists have been intruded by rocks of a rather wide range of composition and texture. These rocks consisted originally of materials ranging from basic to acidic types and have undergone varying degrees of metamorphism along with the schists. Some basic intrusive rocks are now altered to serpentines and contain asbestos, and appear to be almost as old as the surrounding mica schists. Other acidic rocks have been metamorphosed little or not at all, and were injected after the schist had undergone most of its metamorphism. It is therefore evident that intrusive rocks of various kinds have been injected into the schists at different times and have been altered to a degree corresponding to the alteration of the schists since their intrusion. Most of the intrusive masses are small, and no attempt has been made to show the smaller masses on the accompanying map (Pl. III, in pocket). The following petrographic description of the schists is taken from Paige and Knopf:[1]

The schists are thoroughly foliated rocks of medium grain, and show in general no variations in appearance. Under the microscope they are found to comprise garnetiferous mica schists and chlorite-albite schists. The garnetiferous mica schist is composed largely of quartz, which shows powerful strain shadows, muscovite in long laths, chloritized biotite, orthoclase, and garnet altered almost completely to chlorite. In the albite schist soda feldspar is the dominant constituent. The albite poikilitically incloses various other constituents, chief among which is clinozoisite in long, stout prisms, usually oriented parallel to

[1] Paige, Sidney, and Knopf, Adolph, Geologic reconnaissance in the Matanuska and Talkeetna basins, Alaska: U. S. Geol. Survey Bull. 327, pp. 10-11, 1907.

the schistosity. In addition to the albite abundant quartz, crushed and showing strain shadows, is present in considerable amount, with some chlorite and clouds of magnetite dust. Muscovite is but an accidental constituent, and is only found included in the albite plates. Some of the albite schists, however, contain muscovite as an important constituent. Such a schist, examined microscopically, shows large albites in the form of augen, quartz badly crushed and strained, muscovite of a sericitic nature, and chlorite, and is evidently a schist affected by a second period of dynamic activity.

Some serpentine and pyroxenite are included in the mica schist series. The pyroxenite presents a pseudoporphyritic aspect under the microscope, due to crushed plates of monoclinic pyroxene lying embedded in a ground-mass of serpentine. The pyroxene is noteworthy on account of the fine multiple twinning parallel to the orthopinacoid and of the slicing which has taken place along that plane. The shearing of the pyroxenite is probably to be correlated with the movement which crushed the schists.

A specimen collected during the present investigation, when studied in thin section, also proved to be a typical mica schist. The rock contains abundant shreds of white mica, closely associated with magnetite and arranged in lines of foliation. The components bend around and envelop attenuated eyes of granulated quartz showing undulatory extinction and what are probably altered orthoclase crystals. The rock contains some apatite and perhaps some garnet and was probably derived from a granite.

The structure of the schists is complex and can be deciphered only by extremely detailed study. Metamorphism has progressed so far that original characters have been destroyed, and the development of schistosity and cleavage planes has so obscured the old bedding planes that they can no longer be recognized. Observations of strike and dip can be made only on the schistosity, and this has at many places no relation to the original bedding. A study of certain of the igneous dikes in the schists shows that the schists have been closely and irregularly folded and faulted, and the problem is thus still further complicated. It may be said, however, that the schistosity in general strikes northeastward and dips about 45° on either side of the vertical, but the direction of dip and strike are by no means uniform.

THICKNESS.

No idea could be gained of the thickness of the schist series, but the elevation at which it outcrops within the area studied ranges from 2,000 to 4,800 feet. The base of the schist is nowhere exposed, and its downward extension is therefore undetermined; its top has been subjected to erosion at two known periods, and possibly at other times of which there is now no record. It may be safely assumed that the schists reach a maximum thickness of several thousand feet.

ORIGIN AND STRUCTURE.

It is not yet possible to state definitely the mode of origin of the mica schists. Whatever may have been the character of the original rocks of which the schists were formed, they have now been so greatly changed by metamorphism, with accompanying recrystallization of the rock-forming minerals and the production of schistosity, that they have lost all traces of their original character. They bear, however, some resemblance to other schists which consist, in part at least, of altered sediments, and they may therefore consist in part of sedimentary material. In places, however, the schists include igneous rocks, which show varying degrees of metamorphism and which are of later age than the typical mica schist that incloses them. It may therefore be tentatively affirmed that the schists originally consisted of sediments which were intruded by igneous rocks at various times and metamorphosed during two or more periods of deformation. The structural relations of the mica schists to the diorites and gneisses, to the Tertiary sediments, and the unconsolidated Quaternary deposits are shown diagrammatically in the geologic cross sections A–B and C–D, on Plate III (in pocket).

AGE AND CORRELATION.

No fossils have been found in the schists, and none are likely to be found in them, for the processes which altered the rocks to their present condition would almost certainly have destroyed any fossils they may have contained. The age and character of the rocks that underlie the schist are not known. The next succeeding sedimentary beds are of Eocene age, but they were not deposited until the schists had been metamorphosed, intruded, and then subjected to a long period of erosion. The schists are cut by granitic intrusives, which, as will be shown later, are probably of late Lower Jurassic or Middle Jurassic age. Before the granitic rocks were intruded the schists had been metamorphosed to their present condition, so that they must have been formed long before the intrusion. The only definite statement that can be made, however, is that they are of pre-Jurassic age.

Similar schists occur in south-central Alaska near Lake Klutina,[1] on Dadina River near Mount Drum,[2] in the Gulkana River district,[3] in the Iliamna region,[4] and about lower Cook Inlet,[5] but at none of these localities was their age determined.

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[1] Schrader, F. C., A reconnaissance of a part of Prince William Sound and the Copper River district, Alaska: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, p. 410, 1898.

[2] Mendenhall, W. C., Geology of the central Copper River region, Alaska: U. S. Geol. Survey Prof. Paper 41, pp. 27–30, 1905.

[3] Moffit, F. H., Headwater regions of the Gulkana and Susitna rivers, Alaska: U. S. Geol. Survey Bull. 498, pp. 26–27, 1912.

[4] Martin, G. C., and Katz, F. J., A geologic reconnaissance of the Iliamna region, Alaska: U. S. Geol. Survey Bull. 485, pp. 30–32, 1912.

[5] Martin, G. C., Contributions to the geology of Kenai Peninsula: U. S. Geol. Survey Bull., in press.

In the Yukon-Tanana region the Birch Creek schist, which closely resembles the schists of the Willow Creek district in its appearance, lithologic character, and relation to granitic intrusive masses, has a widespread occurrence and is, in part at least, of pre-Ordovician age and perhaps in part pre-Middle Cambrian.[1] Its correlation with the schists here considered is offered only as a suggestion and is at present unsupported by definite evidence. In the lack of conclusive proof the schists of the Willow Creek district are provisionally assigned to the Paleozoic, though they may be even older.

TERTIARY SYSTEM.

ARKOSE, SHALE, AND CONGLOMERATE.

DISTRIBUTION.

A group of rocks consisting of arkose, shale, sandstone, and conglomerate borders the Willow Creek district on its southern edge and forms the youngest group of hard rocks in the area here described. West of Little Susitna River these rocks are confined to the southward-facing flank of Bald Mountain Ridge and to the lowland south of it, where they are in part covered by later glacial deposits. The shape of the surface in the areas in which these rocks occur is due to their structure, for they dip to the south at an angle only a little steeper than the average slope of the mountain front and form a veneer of variable thickness on the underlying gneiss and schist. On the southeast flank of Government Mountain the dip of the beds is less steep than the slope of the mountain face, and the gneiss outcrops in an area from which the sediments have been removed by erosion. In the canyon of Little Susitna River conglomerate, shale, sandstone, and arkose of this group outcrop, forming the canyon walls, but this area is separated from the other areas mapped by a covering of glacial morainal material. East of Little Susitna River this group occupies a broader area and includes the rocks from which the front ridge of the mountains has been carved. There also the beds dip southward on the south flank of the mountains and are in part covered by glacial deposits and in part by still younger rock formations. East of the area here mapped (Pl. III, in pocket) this group of rocks extends for many miles along the mountain front.[2] Its westward extension beyond the Willow Creek district has not been traced.

CHARACTER.

All the Tertiary sediments are well indurated and consist of hard arkose, firm sandstone, shale which in places approaches argillite in character, and conglomerate which varies from a very dense massive

[1] Cairnes, D. D., Geological section along the Yukon-Alaska boundary line between Yukon and Porcupine rivers: Bull. Geol. Soc. America, vol. 25, pp. 179-204, 1913.

[2] Martin, G. C., and Katz, F. J., Geology and coal fields of the lower Matanuska Valley, Alaska: U. S. Geol. Survey Bull. 500, pl. 5, 1912.

bed in which the matrix is as hard as the included pebbles, to a more loosely cemented deposit which on weathering breaks down into sandy gravel.

The basal member of the group is commonly conglomerate with an arkosic matrix, locally very coarse in texture and containing bowlders, the largest a foot or more in diameter, intermingled with cobbles and pebbles. The interstices between the pebbles are filled with arkose, and the whole rock is very hard and shows evidence of metamorphism. Most of the pebbles and bowlders, as well as the arkosic matrix, consist of fragments of igneous rocks derived from the great intrusive mass to the north. Where this conglomerate is most strongly metamorphosed the borders of the bowlders seem to merge indefinitely into the matrix, and the whole rock closely resembles certain phases of the gneiss which it overlies, and from which it is in places hard to distinguish. At other places the basal conglomerate is composed of even-sized cobbles averaging about 6 inches in diameter, is little metamorphosed, and on weathering breaks down by the disintegration of the matrix. At still other places the basal conglomerate is absent, the lowest member being composed of arkose, perhaps containing a few scattered pebbles.

The arkose beds, which form by far the largest part of the group, are composed of the disintegration products of the granitic mass that lies north of and beneath them. They contain practically all the minerals of which the granitic rocks are composed and only a small proportion of material derived from any other sources. Since the igneous mass that supplied this material was weathered largely by mechanical disintegration rather than by chemical decay, and since the detritus was deposited not far from the source of the material, the resulting sedimentary formation closely resembles the original granitic rock in chemical composition. This resemblance has been emphasized by the induration of the sediments, which on hardening have taken on also much of the physical character of the granitic rocks. The arkose therefore bears a very deceptive resemblance to granular igneous rock and could be distinguished from it only with great difficulty if it were not for the presence in the arkose of scattered rounded pebbles and of carbonaceous prints of plant remains.

In the hand specimen the arkose is commonly gray, though locally it may have a greenish cast. It shows all gradations in coarseness from a sandy shale to a fine conglomerate. Some beds might well be termed graywackes; others are impure micaceous sandstones. The gradation from arkose to conglomerate may be gradual, a few small rounded pebbles appearing in the arkose at one place but becoming more abundant farther along until the bed is unquestionably a conglomerate with an arkose matrix. Quartz and feldspar

are its most abundant constituents, but it contains numerous particles of ferromagnesian minerals and both primary and secondary mica.

A typical arkose and a finer-grained graywacke of this group were examined microscopically in thin section. The arkose consists of an interlocking granular aggregate of quartz and feldspar. The quartz crystals are clear, have very irregular borders, and show undulatory extinction due to pressure. The feldspars, which, as shown by their albite twinning, are mostly acid plagioclase, are dusted with kaolin and carry scattered shreds of sericite. They are notably angular in outline, showing no rounding whatever. Some of the quartz crystals have perfect hexagonal outlines, probably due to recrystallization.

The graywacke is an aggregate of rather irregular angular grains of quartz and feldspar knit together by shreds of partly chloritized biotite and containing grains and aggregates of epidote. The rock is a graywacke that has suffered metamorphism, the ferromagnesian minerals having been converted into biotite and epidote.

In places where the arkose has been somewhat metamorphosed and overlies gneiss, the line of contact is obscure and as mapped may be somewhat in error, especially in the vicinity of Government Mountain, on account of the similarity of certain phases of the two rocks.

Toward the top of the Tertiary sediments on the divide between Little Susitna River and Moose Creek the arkose is interbedded with irregular lenses of shale and impure micaceous sandstone. These lenses may locally reach a thickness of a hundred feet or more, but they thin out laterally, and no single bed could be traced for any great distance (Pl. VI, *A*). In the canyon of Little Susitna River a similar series of interbedded conglomerates, shales, arkoses, and micaceous sandstones occurs. There the shales have been much broken and slickensided and are intricately cut by fine calcite veinlets. The conglomerates contain very few bowlders that reach a foot in diameter and few larger than 6 inches, and the average diameter of the pebbles is about 1 inch. The pebbles are composed of quartz, various kinds of igneous rock, chert, and shale.

A characteristic feature of the Tertiary rocks is the presence in them of carbonaceous films, the remains of plants that were buried in the sediments. Such plant remains, although not everywhere abundant, are generally distributed throughout the group and are of great aid in enabling a recognition of the sedimentary character of some of the arkoses. Vegetable matter was locally sufficiently abundant in these rocks to form thin coaly layers, though no workable coal has yet been found in them. Thin coaly beds were seen in the east wall of Little Susitna Valley, 1½ miles below the mouth of Archangel Creek, and on the south slope of Bald Mountain Ridge.

STRUCTURE AND STRATIGRAPHIC RELATIONS.

Between the intrusion of the granitic rocks, which are the youngest rocks that lie beneath the Tertiary arkose beds in the Willow Creek district, and the deposition of sediments a very long time elapsed. During this time the schists, gneisses, and diorites were subjected to some metamorphism and reduced by erosion to a surface of mild relief. It is possible that other sedimentary beds were deposited upon these rocks or at least upon the schists, for Jurassic and Cretaceous sediments are found in the lower Matanuska Valley. If these were ever deposited in the Willow Creek district, however, they were removed by erosion before the Tertiary arkoses were laid down.

The arkosic sediments were deposited in fresh water, presumably first in the lowlands, but spreading laterally into regions of greater altitude as their thickness increased. The basal beds of the group are therefore not everywhere of the same age, for the overlapping edge of the deposits at one place may have been laid down after a great thickness of similar materials had already accumulated in other lower-lying basins. The structural relations of the sediments to the underlying rocks and to the succeeding unconsolidated Quaternary deposits are shown diagrammatically in the geologic cross sections on Plate III (in pocket).

The contact of the Tertiary arkose beds with the underlying formations, whether schists or gneisses, was, wherever observed, depositional, being parallel with the bedding of the sediments, and the straight course followed by the contact line at any given elevation indicates that the surface upon which the Tertiary beds were deposited was fairly level.

At several localities the deposition of the Tertiary sediments was interrupted by flows of basaltic lava. These flows are thin and are individually of small areal extent but were seen at points 11 miles apart. Near the west edge of this area, on the south slope of Bald Mountain Ridge, a lava flow about 50 feet thick occurs very near the base of the Tertiary arkose beds. East of Little Susitna River similar lava flows occur several hundred feet above the base of the Tertiary. If the lava flows at all localities are contemporaneous, then the lowest part of the section exposed east of Little Susitna River is lacking in the western part of the area. On the other hand, if the basal Tertiary beds at both places are contemporaneous and sedimentation at each place was equally rapid, then outpourings of lava occurred at intervals during the accumulation of several hundred feet of sediments.

The Tertiary sediments have been indurated and tilted and slightly folded. The deformation doubtless accompanied the uplift of the Talkeetna Mountains, for the general strike of the Tertiary arkoses is parallel with the mountain front and the dip is toward

the south, away from the mountains. West of Little Susitna River, along the south flank of Bald Mountain Ridge, the sediments strike a few degrees north of east and dip southward at an average angle of about 50°. This is steeper than the average slope of the mountain front, and the sediments form a cover above the older rocks, becoming gradually thinner toward the south. The slope of the south side of Government Mountain, however, is steeper than the dip of the Tertiary beds, and the underlying gneisses have been exposed by erosion in areas south of the sediments. East of Little Susitna River the exposed portion of the arkosic rocks is thicker, though the beds strike in about the same direction as west of that stream and have here also a general dip to the south (Pl. IX, *A*). The monoclinal southward dips are broken by a shallow syncline whose axis runs northeastward from the head of Little Susitna Canyon. In this part of the area the contact of the beds, wherever it could be examined, was a depositional contact, with gneissic rocks beneath. Still farther east, in the lower Matanuska Valley, the arkosic beds are in contact with other Tertiary rocks and with Cretaceous and Jurassic sedimentary beds, but so far as known these relations have been brought about by faulting.[1]

THICKNESS.

The total maximum thickness of the Tertiary sediments is not known, for the beds at their southern edge dip beneath a covering of glacial deposits and their upper limit has not been defined, and the base of this rock group, as exposed in the Willow Creek district, is probably higher in the stratigraphic section than the lowest beds in the basins where the earliest sediments of this group were deposited. From his study of these rocks in the lower Matanuska Valley Martin [2] concludes that the beds exceed 2,000 feet in thickness. On the top of Bald Mountain Ridge, south of the head of Grubstake Gulch, more than 2,000 feet of the series is exposed, and it is elsewhere probably much thicker. There the beds have undergone only simple monoclinal tilting, and the chance that they may have been reduplicated by faulting is small. South of Idaho Peak, on the south side of Little Susitna River, the arkose beds are well exposed up to the divide between that stream and Moose Creek. The sediments dip uniformly to the south except at the divide, where they form a shallow syncline. A measurement of this section indicates that the Tertiary arkosic rocks are over 6,000 feet thick, but such a measurement must not be accepted as final, for the beds are faulted in some degree, and the

[1] Martin, G. C., and Katz, F. J., Geology and coal fields of the lower Matanuska Valley, Alaska: U. S. Geol. Survey Bull. 500, p. 41, 1912.
[2] Idem, p. 42.

The old upland surface.

thickness may therefore appear greater than it actually is. It is certain, however, that the maximum thickness in this district is several thousand feet.

AGE AND CORRELATION.

The age of the Tertiary arkosic sediments has been pretty definitely determined on the evidence of fossil plants collected from them. As the beds are of fresh-water origin, no marine fauna has been found in them, but carbonaceous imprints of the leaves and stems of plants are abundantly distributed throughout them. In most places the fossil plants are too fragmentary or have been too poorly preserved to be identifiable, and no satisfactory collections were made in the Willow Creek district. The eastward extension of the arkosic rocks has, however, yielded more perfect fossils. A collection made by Paige and Knopf [1] in 1906 and identified by F. H. Knowlton contained the following species:

Fossils from Arkose Ridge north of Moose Creek.

Taxodium distichum miocenum Heer.	Ficus? grönlandica? Heer.
Taxodium tinajorum Heer.	Paliurus colombi Heer.
Populus sp.?	Fruits, cf. Leguminosites sp.

Age apparently Kenai.

Another collection from the same formation in Sheep Valley, 6½ miles N. 70° E. of the mouth of Kings River (locality 5900, elevation 4,400 feet), made in 1910 by Martin and Katz,[2] was identified by Arthur Hollick, who reports that it contains *Populus arctica* Heer and *Quercus platania* Heer, of "Arctic Miocene" age (Eocene).

The above determinations seem to definitely correlate the arkosic rocks of the Willow Creek district with the Kenai formation of Cook Inlet, of Eocene age. Beds of like age are widely distributed along the shores of Cook Inlet, in the Matanuska Valley, at many localities around the borders of Susitna basin, and at other places in Alaska, and usually contain some lignitic coal.

The correlation of a part of the Eocene arkosic sediments of the Willow Creek district with those of the lower Matanuska Valley [3] is definitely made, for the rocks are directly continuous between the two areas. It is not certain, however, that the arkosic rocks here described are the equivalent of the whole arkosic group as described by Martin. Some beds may be lacking, or horizons represented in the Willow Creek district may not appear farther east. In both districts, however, the beds are dominantly arkosic.

[1] Paige, Sidney, and Knopf, Adolph, op. cit., p. 26.

[2] Martin, G. C., and Katz, F. J., Geology and coal fields of the lower Matanuska Valley, Alaska: Bull. U. S. Geol. Survey No. 500, p. 42, 1912.

[3] Idem, pp. 39–42.

QUATERNARY SYSTEM.

PREGLACIAL CONDITIONS.

The period of deposition of the Eocene arkosic sediments, the youngest hard rocks of the Willow Creek district, was followed by a long period during which the beds were indurated, deformed, and eroded. In that period the arkosic rocks east of this area, in the Matanuska Valley, were buried beneath a thick covering of later materials, including the coal-bearing Chickaloon formation (of Eocene age), the Eska conglomerate (of Tertiary, possibly Miocene age), and several hundred feet of volcanic rocks. These later formations may have been deposited to some extent in the Willow Creek district also, but if so, they have since been removed by erosion. At any rate, in preglacial times the rocks of this district were hardened and deformed to about their present condition. The Talkeetna Mountain range had then about the same general elevation as it has to-day, but its appearance must have been greatly different. The surface forms were developed by the ordinary processes of erosion, chief among which was stream cutting and transportation. The mountains contained well-developed river systems, and were reduced by the streams to maturity, the stream valleys being predominantly of V shape. Most of the valleys were not so deep as they now are, the slopes of the valley sides were more gentle, and the ridges were rounded and smoothed. Some idea of the appearance of the old upland surface may be had from the parts of it that still remain. (See Pl. IX, *B*, p. 34.) The streams, flowing in valleys which had been developed by stream erosion, probably followed somewhat crooked courses, winding back and forth around spurs which projected from the bordering ridges into the valleys from both sides. There must have been present also large accumulations of soil and the products of rock weathering on the gentler slopes, of talus below the cliffs, and of stream deposits along the valley floors.

GLACIAL EPOCH.

ADVANCE OF THE ICE.

The beginning of glaciation in Alaska has not yet been correlated with any particular glacial stage in other parts of the world. In the northern part of the United States at several different periods during Quaternary time glaciers grew to great size and covered large areas. In Alaska no convincing evidence has so far been found that Quaternary glacial advances antedated the last great glaciation, the effects of which are so widespread. In mountainous regions such evidence would be difficult to obtain, for the ice at the time of the last glacial advance was so deep and its erosive action was so great that it would have removed or buried any earlier glacial deposits, and would have so modified the topography developed by the earlier ice as to make its

recognition difficult. If, however, in earlier glacial stages the ice had been more extensive than it was during the last great advance it should have left definite traces either on the topography of the region or as deposits beyond the limits to which the last glaciers reached. Up to the present time no such evidence has been found, and it seems probable that at no time have the glaciers greatly exceeded in size those which developed during the last great ice advance.

The beginning of glaciation in Alaska was brought about by some decided change in climate, probably involving both a decrease in the temperature and an increase in precipitation. As this change progressed, snowbanks accumulated on the protected slopes of the higher mountains and grew until they formed glaciers. Each elevated valley head finally contained a glacier, and these small ice fields gradually lengthened and extended downward, joining in the main valleys to form larger ice tongues. The glaciers probably did not grow continuously, doubtless they oscillated back and forth, each advance being followed by a pause or even by a recession, but the total result of all the movements was growth of the ice fields, both in length and thickness. The advancing ice, moving over surfaces which had long been exposed to weathering, found much loose surface material, such as soil, talus, and the valley bottom deposits of streams, and it readily picked up and removed this unconsolidated material. The bedrock surfaces thus exposed were then attacked, for the thick ice streams, which contained abundant fragments of rock, pressed down with tremendous weight upon their beds, and in their slow forward movement dragged the embedded rocks as cutting tools along the slopes which inclosed them. Each glacier, by freezing to its bed and then moving forward, tore loose great blocks of rock from its channel, and additional detrital material, falling upon the ice surface, was carried slowly down the valley. The tendency of a valley glacier is to attack most vigorously all projecting hills and spurs which obstruct its course, and by the removal of these interruptions to produce a great trough, U-shaped in cross section, and following straight lines or sweeping curves. The multitude of small tributary glaciers at the valley heads cut back their basins toward the divides, developed cirques, and by their combined action reduced the original smoothed and rounded ridges to ragged and broken crests.

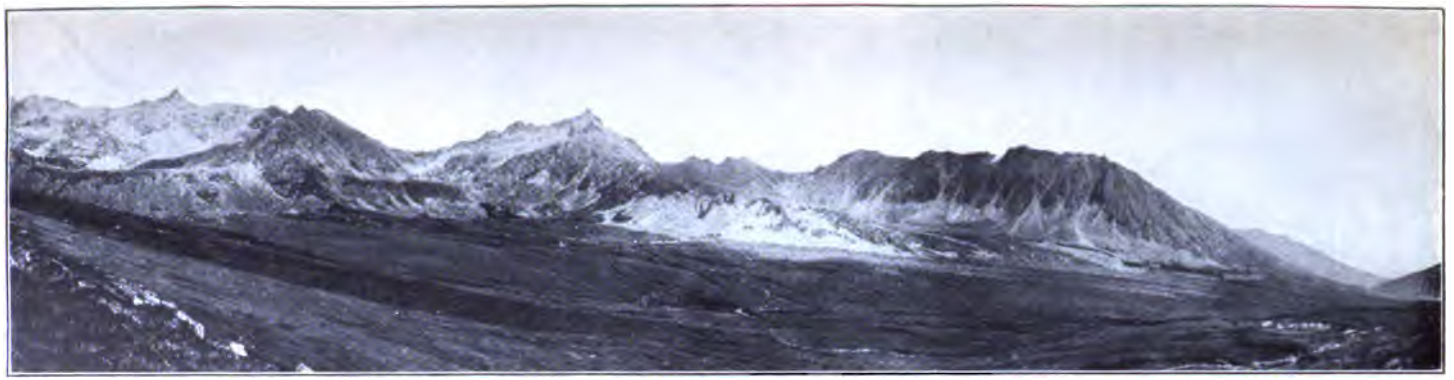
No exact measure is available of the amount of material that was removed by glacial erosion, but there can be no doubt that the valleys were widened and greatly deepened; and the widespread blanket of glacial deposits which mantles the lowlands bears testimony to the effectiveness of this method of erosion in the mountains from which this material was brought. In the Willow Creek district practically all the streams that join the main drainage lines lie in valleys that show a noticeable topographic discordance with the main valleys.

These are known as hanging valleys. The main trough of Little Susitna River (disregarding the postglacial cut of the stream at the canyon) joins the lowland to the south with a discordance of over 200 feet. Willow Creek, at the west border of the Talkeetna Mountains, falls 800 feet in about 4 miles, although the stream gradient above is much more gentle. Many of the tributaries of Little Susitna River emerge from hanging valleys to descend steeply before joining the river. The glacial trough of Fishhook Creek hangs more than a thousand feet above the bottom of the main river valley, and is itself bordered by a number of hanging cirques. (See Pl. X.) All the principal tributaries of Willow Creek, namely, Shorty, Craigie, Wet, Grubstake, and Homestake creeks, flow in hanging valleys and have falls or cascades at their lower ends. If the discordance between the mouth of a hanging valley and the stream which it joins can be used as a measure of the amount of glacial deepening, then Willow Creek below the mouth of Craigie must have been lowered 400 feet by glacial erosion and Little Susitna Valley at the mouth of Fishhook almost twice that amount.

EXTENT OF GLACIATION.

The Willow Creek district was but a small portion of the supply field for the great glaciers which once buried most of that part of Alaska which lies within the arc of the Alaska Range. All the mountains which surround Susitna basin contributed to a huge ice field which filled that basin and extended southward to tidewater in Cook Inlet. The Talkeetna Mountains furnished many tributary glaciers, and an important feeder came down the Matanuska Valley. Only the higher mountain peaks and ridges broke the great expanse of moving ice. At the same time the Copper River basin was similarly glaciated, and the two basins were connected by continuous ice fields through the Matanuska Valley and the upper Susitna Valley. The larger valleys merely afforded passageways for the downward-moving ice flood, but most of the snow accumulated in the small valleys among the peaks of the mountain ranges. There the snowfall was greatest, the slopes were steep, and the ice, confined within narrow valleys, moved rapidly and was able to accomplish the greatest erosion. In the broad basin of Susitna River, where many glaciers came together, the ice spread out and, becoming more sluggish, lost much of its erosive power, and the accumulated burden of rock waste, gathered by the tributary glaciers, was gradually deposited over the basin floor.

The vigor of any particular mountain glacier depends to a large extent upon the size of its basin, the height of the surrounding mountains, and its exposure to the sun. In an area of equal snowfall a valley surrounded by high mountains and having a northern slope



A. NORTHEAST VALLEY WALL OF UPPER FISHHOOK CREEK.

The view shows three tributary hanging valleys. The top of one stamp mill may be seen in the lower right corner and another camp and mill appear just above it.

B. HEAD OF FISHHOOK VALLEY FROM THE SOUTHEAST.

will support a larger glacier than another valley of equal size surrounded by lower mountains and having a slope more directly exposed to the sun's rays. Little Susitna Valley is surrounded near its head by high mountains, and in spite of its southern exposure it once sent down a strong glacier to join the ice from Matanuska Valley. For so long as it joined the Matanuska Glacier the level of the ice surface in Little Susitna Valley was determined by the height to which the Matanuska Glacier dammed that valley. At the period of its greatest thickness the Matanuska Glacier stood up to an elevation of about 3,600 feet on the south flank of Government Mountain and dammed back the Little Susitna Glacier to that height. The ice surface increased in elevation to the north, and at the mouth of Reed Creek reached an elevation of about 4,000 feet.

The basin of Willow Creek is not so large as that of the Little Susitna, nor are the surrounding mountains so high, and the glacier that occupied it was smaller and less vigorous. All its headward tributaries lie in glacial cirques, and the main valley shows strongly the effects of glacial erosion, but at the mouth of Wet Gulch the maximum thickness reached by the glacier was about 1,000 feet, as compared with a thickness of 2,000 feet at the forks of the Little Susitna. The north slope of Bald Mountain ridge supported a number of glaciers, each of which eroded its basin into a glacial cirque. The south side of the same ridge had no local glaciers, except perhaps one at the head of Government Creek. Toward its west end this ridge was not high enough for glaciers to form upon it, and its crest shows the type of broad, smooth ridge which probably characterized the whole region before the glaciers modified its topography. Craigie Creek valley is a fine glacial trough, which has six or more small tributary cirques on its south side but none on the north. The Willow Creek Glacier at the time of its greatest development joined the Great Susitna Glacier.

RETREAT OF THE ICE.

After the ice fields had reached their maximum thickness and size the climate gradually changed. The mean annual temperature probably increased a few degrees and perhaps the precipitation diminished somewhat. From whatever cause, the conditions for ice formation became less favorable and the edges of the glaciers began slowly to withdraw. The retreat, like the advance, was probably by no means continuous, but as the result of numerous recessions, pauses, and readvances the area of the ice fields became gradually smaller and land surfaces which had been covered by ice were again bared. As the main glaciers in the larger valleys became shorter and narrower many tributary ice streams from lateral valleys were detached, and these in turn retreated up their valleys and were sepa-

rated into a great number of smaller valley glaciers, many of which melted away and disappeared completely.

Although the conditions for ice accumulation are now much less favorable than they were during the period of maximum glaciation, many parts of the high mountains that border the Susitna basin are still occupied by large and active glaciers, the remnants of the much greater ice fields that existed at the time of great glaciation. Knik Glacier, at the head of Knik River, within plain sight of the southern part of the Willow Creek district, is a large valley glacier which extends down to an elevation less than 200 feet above sea level. The Chugach, Kenai, and Chigmit mountains and the Alaska Range support large ice fields, and in the higher parts of the Talkeetna Mountains there are many smaller but still vigorous valley glaciers. Within the Willow Creek district there are five small glaciers, all lying in the basin of Little Susitna River. Two of these drain into Archangel Creek and two into Reed Creek. The one which forms the source of Little Susitna River is the largest, and when most active discharges enough silt to cloud the waters of the river. The others are small and inactive.

GLACIAL DEPOSITS.

The rock waste transported by glaciers is ultimately dropped by the ice, and it may be deposited as glacial moraines or may be fed to the streams discharging from the melting ice and deposited as glacial outwash gravel and silt. The ridgelike accumulations of detritus at the front edge of a glacier are known as terminal moraines and their characteristic hummock and hollow topography, many of the hollows being occupied by lakes, may be seen in many places in the lowlands between Knik Arm and Susitna River. Within the mountains of this district terminal moraines are not developed, and their absence has been noted in a number of severely glaciated mountain ranges of Alaska. A study of many active valley glaciers which terminate in narrow valleys has shown that almost every stream at the lower end of the glacier where the rock waste is most rapidly deposited, is directed by the slope of the valley walls against the edge of the glacier, and is admirably placed to remove the morainic material as fast as it is dropped by the ice. The absence of terminal moraine ridges in this district is best explained by assuming that they were never conspicuously developed. Lateral moraines deposited along the sides of the glaciers near their lower ends were seen in a few favorably situated places. These locally appear as benches, and there may be several, one above the other, the highest having been built first and the lower ones at a later stage, during the retreat of the ice. (See Pl. VIII, *B*, p. 26.)

When the ice was thickest and its movement was most rapid, the mountain glaciers doubtless severely eroded and deepened their channels, but at a later period, when the ice had thinned, erosion gave place to deposition. Much of the rock waste incorporated in the glaciers was deposited beneath the ice as glacial till upon the bedrock, which had before been worn and eroded. The glacial till is composed of a mixture of all the detritus carried by the ice and consists of a tough clay in which are incorporated bowlders, pebbles, and angular pieces of rock, the whole assemblage being free from any such assortment as characterizes deposits laid down in water. The areas of morainal deposits, as shown on Plate III, are covered with glacial till, but include only those parts of the district in which the glacial materials are thick enough to hide completely the underlying hard rock formations. Over many other parts of the area there are smaller accumulations of moraine, but wherever they were too small to mask the underlying bedrock topography they were not mapped. The lowlands on the south border of the district are covered with glacial materials, and the bedrock of the mountain front is overlain by moraine up to an elevation of about 2,000 feet. Similar deposits cover many square miles of the basin of Little Susitna River above the canyon, and few bedrock exposures occur either in the valley bottom or on its sides below a height of 2,500 feet. The present gorge of the river above the canyon and the steep inner valley of lower Fishhook Creek have been cut deep into the glacial material without exposing the underlying rocks. A few of the tributary valleys contain considerable accumulations of moraine, but in most of the surrounding cirques the bedrock is exposed at many places. The valley floors of Willow Creek and some of its larger tributaries are likewise covered with a mantle of glacial deposits, but the covering is there comparatively thin and has in places been removed by stream cutting.

Here and there within this district deposits of stream-washed gravels are associated with the glacial till, but they are not of great extent, and on the map (Pl. III) they have not been separated from the morainal deposits. Most of the stream gravels of glacial origin were carried beyond the borders of this district and deposited in the lowland areas.

POSTGLACIAL EROSION.

When the glaciers retreated and bared the valleys which they had first eroded and then partly refilled with unconsolidated deposits, the valley gradients were no longer adjusted to the streams. For some stretches the stream grades were steeper than they had formerly been, or the streams flowed upon easily eroded glacial deposits where formerly they had flowed over hard rock. In other places the gradients had been flattened. Each stream, in again occupying a

regraded and changed valley, set about the task of reestablishing a normal stream gradient adapted to the size of the stream, the character of the material, and the amount of load. Under postglacial conditions the tendency of most of the streams in this district has been to intrench themselves.

The length of the period which has elapsed since the glacial ice disappeared and during which the surface has again been exposed to weathering and stream erosion is not the same for all parts of this district. A few small glaciers still survive, and their basins may be said to be still in the glacial epoch. The glaciers remained at the valley heads of the higher mountains long after the lower parts of their basins were free of ice. This whole district, however, gives one the impression that glaciation there has been comparatively recent. It is only along the stream courses that postglacial erosion has destroyed the shape of the surface as left by the ice. The greatest amount of postglacial erosion is to be seen at the canyon of Little Susitna River, where that stream has cut a gorge several hundred feet deep through the glacial deposits and into the Tertiary arkosic rocks. Above the canyon the stream has intrenched itself in the glacial materials, and the high benches on either side show the position of the valley floor as left by the ice. The amount of postglacial deepening of the valley decreases upstream, and in the cirque heads the stream cuts are shallow or completely lacking. That part of Fishhook Creek that flows at right angles to Little Susitna River is sharply intrenched in the moraine for the grade there is steep and the current rapid. Between the mouth of Fishhook Creek and the canyon the steep gulches tributary to Little Susitna River, both from the east and west, have been cut into the glacial deposits, and on the east much of the unconsolidated materials have been removed. In the Willow Creek basin postglacial erosion has accomplished little. The main creek has cut a shallow canyon for a part of its length, but the broad U shape of the valley has been little changed. Shorty, Craigie, Wet, Grubstake, and Homestake creeks have cut sharp canyons through the glacial deposits into hard rock for short distances near their mouths, where the stream gradients are steepest.

Throughout the district as a whole the surface forms are to-day much the same as when first uncovered by the ice. Relatively small stream trenches and gullies and rather inconspicuous accumulations of talus are the measure of weathering and erosion in postglacial times.

PRESENT STREAM GRAVELS.

Since the great ice fields retreated from this district the streams throughout most of their courses have been lowering their channels into the deposits left by the ice, and stream deposition has been unimportant. The present stream gravels are therefore in most places

A. BED OF REED CREEK.

Bowlders are quartz diorite.

B. PEAKS OF ALTERED AND SOMEWHAT GNEISSIC DIORITE ON DIVIDE BETWEEN LITTLE SUSITNA RIVER AND MOOSE CREEK.

A. BLOCK OF GNEISSIC DIORITE CUT BY VEINLETS OF QUARTZ.

B. TUNNEL OF ALASKA GOLD QUARTZ MINING CO. ON GRANITE MOUNTAIN.

Shows two prominent sets of joints in quartz diorite. The veins lie along joints of the set which dips to the left.

not much wider than the streams that flow over them and are thus too small in area to be shown on the accompanying map (Pl. III, in pocket). Through the canyon Little Susitna River flows at the bottom of a rock-cut gorge, and the only stream-washed materials are the large bowlders with which the channel is filled. From the head of the rock canyon to the mouth of Fishhook Creek the channel is cut into glacial deposits, and in this stretch the stream flat at few places exceeds 100 feet in width, and the stream gravels consist of bowlders derived from the glacial till. Above Fishhook Creek the stream flat is somewhat wider, although the width of the narrow strip of alluvium shown is somewhat exaggerated on Plate III. The stream gradient in this district is so steep that the finer material derived from stream cutting has been quickly removed, and only the coarser material, consisting of coarse cobbles and large bowlders of diorite, arkose, and conglomerate, has remained. None of the tributaries of Little Susitna River have important recent gravel deposits, and all of them flow through channels filled with large bowlders. (See Pl. XI, *A*.)

Willow Creek has built up a valley floor of stream gravels below the mouth of Homestake Creek, and the stream flat gradually increases in width toward the west. The low gradient of the valley here has permitted the deposition of gravels derived from the postglacial cuts of the stream above. The stream deposits consist for the most part of cobbles, finer gravel, and sand, but include numerous bowlders a foot or two in diameter and a few larger bowlders. Grubstake and Wet gulches contain considerable deposits of stream-laid material in the intermediate portions of their valleys between the steep lower stretches and the cirques in which they head.

IGNEOUS ROCKS.

GRANITIC AND GNEISSIC ROCKS.

DISTRIBUTION.

As has already been stated, the northern half of this district consists of granitic intrusive rocks, which are a part of the great intrusive mass that comprises a large portion of the Talkeetna Mountains. As mapped by Paige and Knopf [1] the area in which these rocks predominate measures about 35 by 50 miles, and the Willow Creek district lies on its southern edge. The upper basins of Shorty, Craigie, Willow, and Fishhook creeks lie within this area; the basins of Archangel and Reed creeks contain no other rocks, and probably the entire headward portion of Little Susitna Valley is eroded into the intrusive mass, for all the stream bowlders were derived from granitic rocks. Between the head of Willow Creek and the east edge of this

[1] Paige, Sidney, and Knopf, Adolph, Geologic reconnaissance in the Matanuska and Talkeetna basins, Alaska: U. S. Geol. Survey Bull. 327, Pl. II, 1907.

district the granitic rocks merge, along their southern border, into gneisses, which have been carved into a rugged topography resembling that of the unaltered diorite mass. (See Pl. XI, *B*.) In places this transition from unaltered granitic rocks to gneisses appears to be gradual, but where best developed the gneisses are notably different in appearance from the unaltered diorites. Isolated areas of gneisses have been mapped along the summit of Bald Mountain Ridge, on Government Mountain, and in the gulches tributary to the Little Susitna from the east, and well-developed gneisses occur east and south of that river, above the mouth of Reed Creek.

CHARACTER OF DIORITES.

As determined by a microscopic study of the rocks in thin section, the granitic rocks were found to consist for the most part of quartz diorites. These range from rocks in which plagioclase feldspars occur to the exclusion of the alkaline feldspars to types in which the two classes of feldspar are approximately equal in amount and which might be called quartz monzonites or granodiorites. Sections examined include unquestioned diorites, quartz diorites, and diorites with monzonitic tendencies, but for the purposes of this description the narrower subdivisions have been omitted, and the rocks of this general type are all designated quartz diorites. They have undergone various degrees of alteration and grade into the gneissic and schistose types, but in most thin sections the original dioritic character of the rock can still be recognized. Certain rocks show in the field a coarsely crystalline mass, including irregular bodies of a rather fine-grained grayish material, quite different in appearance from the surrounding coarse diorite. Microscopic study, however, shows that both the coarse matrix and the finer-grained inclusions have the same petrographic composition, the difference in appearance being altogether due to the size of the crystals that compose the mass.

The principal minerals of the quartz diorites are hornblende, feldspars, quartz, and biotite, some chlorite, and pyroxene, and smaller amounts of accessory minerals. These minerals are described individually below:

Hornblende.—The hornblende commonly occurs as anhedral, subhedral, or ragged prisms or long laths, predominantly dark green but varying to light green and yellowish or bluish green. Many of the crystal edges are penetrated by crystals of feldspar and quartz, and these also may be poikilitically included within the hornblende. The hornblende often shows twinning, and in places contains shreds of biotite and grains of magnetite and quartz. In many specimens areas of chlorite, calcite, and magnetite probably represent altered hornblende crystals.

Feldspars.—The feldspars are predominantly plagioclase, ranging from albite through oligoclase and andesine to labradorite. Carlsbad, pericline, and albite twinning is common, and many of the crystals contain kaolin and shreds of white mica. White mica is a common alteration product. Orthoclase or microcline is present in varying amounts in many specimens.

Quartz.—Quartz grains of irregular outline appear in most of the diorites, though in varying amount. Undulatory extinction or strain shadows characterize the quartz in areas in which the rocks have been metamorphosed.

Biotite.—Strongly pleochroic biotite in brown and greenish colors is generally present in shreds or leaves. It has been locally altered to chlorite.

Chlorite.—Scattered patches and shreds of green pleochroic chlorite were seen in a number of specimens.

Pyroxene.—Monoclinic, faintly pleochroic pyroxene, of pale-green color, with an extinction angle of about 31°, was seen as scattered grains and irregular crystals in one specimen.

Accessory minerals.—The most common accessory minerals are apatite, magnetite, and titanite, with occasional small crystals of zircon and epidote. It is worthy of note that the granitic intrusives of the Coast Range of southeastern Alaska are characterized by a large amount of titanite, and this mineral has also been frequently observed in the granites and diorites of the Alaskan Range.

CHARACTER OF GNEISSES.

When studied in thin section the gneisses are found to consist almost exclusively of rocks which might well have been derived by metamorphic processes from quartz diorites. Many specimens taken from areas in which a strong gneissic structure was evident were found to be composed of somewhat altered diorite, differing from the more massive forms principally in their content of the more abundant alteration products. The hornblende has in part been altered to chlorite and magnetite, and the feldspars to kaolin and white mica, both of which contain considerable secondary chlorite, magnetite, and epidote. The quartz is somewhat crushed and shows strain shadows. The metamorphism has locally resulted in the development of a large amount of hornblende, certain phases of the gneiss being coarse-grained hornblendites containing only small amounts of other components. On the south flank of Government Mountain the gneisses show the greatest degree of metamorphism, and some of them might well be called hornblende schists. One specimen of this character is composed of subhedral to anhedral hornblende prisms of green and yellow tones, more or less aligned

and separated by irregular grains of quartz and feldspar carrying apatite needles. The feldspar is much altered but appears to be plagioclase. Magnetite occurs in scattered grains.

AGE AND RELATIONS.

The relations of the diorites and gneisses to the associated rocks are shown diagrammatically in the geologic cross sections A–B, C–D, and E–F on Plate III (in pocket). The granitic rocks and the gneisses, although quite distinct in the areas of their typical development, in places seem to grade into one another, and in the field work on which this report is based it was found to be impracticable to draw a sharp line of separation between them. In the accompanying geologic map (Pl. III) those areas in which gneissic rocks occur have been indicated by an overprinted pattern. In spite of the fact that the edges of the granitic mass at some localities show considerable metamorphism and are gneissic, the rocks of the typical gneiss areas, as on Government Mountain and Bald Mountain Ridge, as well as the rocks that immediately underlie the arkoses east of Little Susitna River, are highly metamorphosed, have a banded appearance, and in places contain an intricate network of quartz veinlets (Pl. XII, *A*), so that they are possibly older than the main granitic mass. The close relations between the gneisses west of Little Susitna River and the mica schists of that area also lend weight to the supposition that the typical gneisses are older than the rocks of the main granitic intrusion and were metamorphosed before its magma was injected. On the other hand, the borders of the great intrusive mass have certainly suffered some metamorphism, and it is possible that the metamorphism was most intense just south of the border of the intrusive rocks, and that the gneisses are the metamorphic equivalent of the granitic rocks. As has been shown, the gneisses when studied microscopically seem to consist for the most part of altered diorites or of rocks that might have been derived from diorites by metamorphism. If, therefore, they are older than the massive diorites, there must have been two periods of dioritic intrusion, and no definite evidence that there were two periods has yet been found in this region. More detailed work will be necessary to settle this question.

The gneisses are certainly younger than the mica schists, for they lie upon the schists and are less severely metamorphosed than those rocks. It may be that the contact between the gneiss and the mica schist is a fault contact, but this was not determined. At any rate, the lesser metamorphism of the gneiss indicates that it is younger than the schist. The gneisses were formerly more widely distributed than they are now, for pre-Tertiary erosion stripped them away from parts of the underlying mass of mica schist, and the later Tertiary arkosic

rocks cover much of the gneiss area. The granitic rocks are also younger than the mica schists and may be younger than some of the gneisses, for they distinctly cut the mica schists and perhaps are intrusive into a part of the gneisses. Both the gneisses and the granitic intrusives are considerably older than the Tertiary rocks. The arkosic rocks, which here form the base of the Tertiary system, were laid down upon a comparatively level erosion surface formed of mica schist, gneiss, and granitic rocks, contain recognizable pebbles of the underlying formations, and are believed to be composed almost exclusively of material derived from this surface by disintegration. The contact between the Tertiary rocks and the underlying formations is in this district a depositional contact and lies parallel to the bedding of the sediments. The evidence obtained in this district therefore shows that the gneisses and the granitic rocks are older than the base of the Tertiary and younger than the mica schists, the age of which is not known.

The age of the great intrusive mass of granitic rocks can, however, be determined more definitely by comparison with other areas in which more conclusive evidence has been obtained. In the upper Matanuska Valley Paige and Knopf [1] found Jurassic rocks containing bowlders of similar composition to the main granitic intrusive, although a smaller outlying granitic intrusive cuts rocks that were then considered Middle Jurassic but are now assigned to the Lower Jurassic. They therefore regarded the great Talkeetna Mountain batholith as Middle Jurassic. It has not yet been proved, however, that the intrusive which cuts the Lower Jurassic is contemporaneous with the main Talkeetna intrusive, so their conclusion is still open to question. Martin and Katz [2] determined the age of a part, at least, of the granitic rocks in the Iliamna region as late Lower Jurassic or early Middle Jurassic, and as this determination coincides rather closely with the conclusion reached by Paige and Knopf, the great Talkeetna intrusion is provisionally assigned to the early Middle Jurassic.

GABBROS.

In the eastern part of the district here considered, near the southern edge of the area of intrusive rocks, there are local patches of intrusive rocks of gabbroic character. Some of these are massive and little altered; others have been severely metamorphosed and have become somewhat gneissic. A study of one of the more massive gabbros in thin section showed a few stout, irregular, nearly colorless augite pyroxene prisms, some of which were partly altered to hornblende, showing a granular nucleus of pyroxene surrounded by hornblende.

[1] Paige, Sidney, and Knopf, Adolph, Geologic reconnaissance in the Matanuska and Talkeetna basins, Alaska: U. S. Geol. Survey Bull. 327, p. 20, 1907.

[2] Martin, G. C., and Katz, F. J., A geologic reconnaissance of the Iliamna region, Alaska: U. S. Geol. Survey Bull. 485, p. 76, 1911.

Hornblende in brown to green anhedral prisms is more abundant than augite, and much of it is probably derived from the augite. The rock contains rounded areas composed largely of a mixture of serpentine and magnetite, which may represent altered olivine crystals. Another somewhat metamorphosed gabbro contains monoclinic pyroxene, probably augite, of a pale-green color, and plagioclase feldspars, dominantly andesine, though some orthoclase may be present. Accessory minerals are represented by apatite and magnetite.

DIKES.

Though not abundant, dikes that cut the diorites, the gneisses, and the mica schists were seen in many parts of the district, but most of them are only a few feet wide and occur in places where their longitudinal extent can be traced for only short distances. Their areal extent is small, and none of those seen were large enough to justify their representation on a map of the scale of Plate III. The dike rocks differ considerably in appearance from one another, but most of them are of much the same mineralogic composition and were probably derived from the same magma that formed the quartz diorite intrusions. Most of the dikes may be classified as alaskite, being fine-grained aggregates of quartz and feldspar that include only small amounts of dark minerals. The quartz occurs as fine, irregular granules, many of them showing strain shadows, interlocked with anhedral and subhedral feldspars. Most of the feldspars are orthoclase, though some are plagioclase, and many are dusted with kaolin. Shreds of chlorite and minor amounts of apatite, epidote, and clinozoisite occur in some dikes, and one showed numerous scattered, irregular crystals of tourmaline.

A more basic dike cuts the quartz diorite on the property of the Gold Bullion Mining Co. This dike contains abundant laths and prisms of greenish-brown, moderately pleochroic hornblende, which is associated with a little magnetite and shows many twinned crystals. The hornblende is set in a groundmass whose constituents can be determined with difficulty, but which is probably for the most part feldspar. Owing to the uncertainty in regard to the composition of the groundmass, the rock can not now be classified.

LAVA FLOWS.

At several localities within the district basaltic lava flows are interbedded with the Tertiary sediments. (See p. 33.) Their areal extent, so far as it could be determined, is shown on Plate III (in pocket). The individual flows have covered only small areas, and none of them is much more than 50 feet thick. That they were actually flows rather than intrusive sills was proved, in one place at least, by the occurrence of fragments of lava in a conglomerate that lay immediately above the flow.

The Bald Mountain trail, at a point a mile southwest of the summit of the ridge, crosses a lava flow that is interbedded in the Tertiary rocks. The lava consists of a basalt having diabasic tendencies and of less completely crystallized amygdaloidal basalts. A thin section of the diabasic phase showed the presence of plagioclase, pyroxene, olivine(?), magnetite, and serpentine. The plagioclase feldspar occurs as laths of labradorite arranged at random in an ophitic matrix of ferromagnesian constituents, and shows albite and carlsbad twinning. Some larger laths may be regarded as phenocrysts. The pyroxene, which occurs in grains and anhedral prisms of pale-violet color, is more or less penetrated by the feldspars and in places fills interstices between them. It is probably a titaniferous augite. Scattered areas now composed principally of serpentinous material may represent original olivine crystals. Grains of magnetite occur here and there. A few areas of concentric fibers of serpentine may represent altered interstitial glass, and in addition there is much greenish, granular to platy serpentinous material.

West of the mouth of Fishhook Creek there is another lava flow, also interbedded with arkose (Pl. III). It, too, is a basalt, but is more andesitic. The abundant plagioclase, which occurs in small lath-shaped crystals, is set in green serpentine and includes grains of magnetite and epidote. The serpentine represents an alteration of pyroxene, probably augite. The rock contains considerable epidote and abundant rounded amygdules, most of which are lined with green serpentine in radiating fibers, but one filled with a granular aggregate of epidote with some magnetite was seen. The rock is so much altered that it is difficult to determine whether it should be classified as an andesite or a basalt, but in the apparent absence of olivine it is here called an andesitic basalt.

The stratigraphic position of these lava flows, interbedded with Eocene sediments, shows definitely that they are of Eocene age. They resemble in field appearance the basaltic lavas of the lower Matanuska Valley,[1] but clearly antedate those, which are possibly of post-Miocene age.

MINERAL RESOURCES.

HISTORY OF MINING.

Although placer gold was discovered on Cook Inlet in 1848 by an expedition of the Russian American Co. and a few ounces of gold was recovered, at that time mining did not prove to be commercially successful and was discontinued. Forty years later, in 1888, American prospectors discovered gold on Turnagain Arm, near Hope, and

[1] Martin, G. C., and Katz, F. J., Geology and coal fields of the lower Matanuska Valley, Alaska: U. S. Geol. Survey Bull. 500, pp. 54-55, 1912.

by 1895 the mining industry in that district was firmly established. The spectacular rise of the Yukon gold camps in 1897 and 1898 brought a great influx of prospectors to the region, and their activities were spread over a great area of previously unknown country. Prospectors working northward from Cook Inlet first visited the Willow Creek district in 1897, and the first placer claims were staked that year. Placer mining in this district has so far been confined to a small area on Grubstake and Willow creeks, and the history of developments there is given on pages 52–55 of this bulletin.

In most parts of Alaska the efforts of the earliest prospectors were directed exclusively to the search for placer gold, for placer gold can be quickly recovered by primitive means and with the investment of little capital. The search for lode deposits almost always follows somewhat tardily after the placer prospecting, for the development of a lode mine requires a considerable investment in the driving of shafts and tunnels in rock, in the purchase and transportation of supplies and machinery, and, except for free milling gold, in the reduction and marketing of the product.

Gold quartz claims in the Willow Creek district were first located in the basin of Fishhook Creek, on September 16, 1906, by Robert Hatcher, who had come into the district to trap and prospect. These, together with others located later, developed into the mine of the Alaska Free Gold Mining Co. In July, 1907, the first claims of the Gold Bullion Mining Co. were staked, and soon afterward the veins of the Alaska Gold Quartz Mining Co. were located. These three properties have since supplied almost all the production of the district. In 1909 prospecting was actively carried on and many claims were staked, most of which were later abandoned without much development work. One or two veins staked that year were, however, considered to be of sufficient promise to warrant the driving of adit tunnels. Of these the property of the Matanuska Gold Mining Co. has since been prospected vigorously, and a number of tunnels were driven, but the company became involved in litigation and has so far produced nothing. In the years 1910 and 1911 prospecting in the district was continued, but none of the discoveries then made have since been developed. In 1912 at least two promising discoveries were made, and others in 1913.

The first stamp mill to be installed in the district was a three-stamp prospecting mill, put into operation in 1908 on the property of the Alaska Gold Quartz Mining Co. The following year the Gold Bullion mill, equipped with two stamps, was completed. Additional units of five stamps at the Gold Bullion and one at the Alaska Gold Quartz mine were put into operation in 1911, and the Lane mill of the Alaska Free Gold mine started crushing ore in August, 1912. No

mills were built in 1913, but two of the reduction plants were made larger in 1914.

The location of the more important mines and prospects is given on Plate III (in pocket), and the position of the same localities, together with a number of prospects not definitely located on the topographic sheet, is shown on the drainage map (fig. 3).

A number of publications which contain descriptions of the geology and mineral resources of this district have appeared from time to time. The earliest of these reports, issued before the discovery of

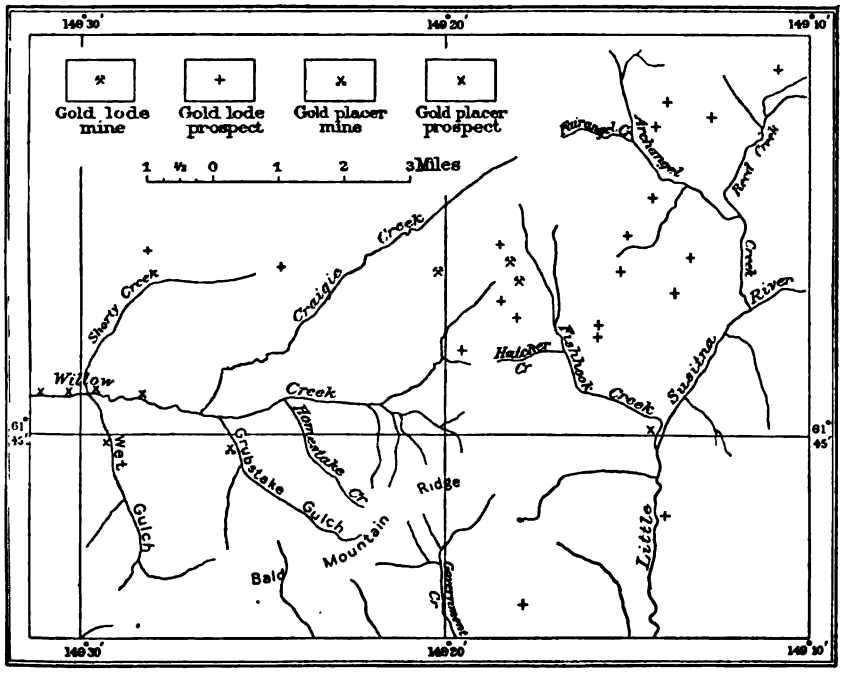


FIGURE 3.—Drainage map of part of Willow Creek district, showing location of mines and prospects.

gold quartz had been made, were by Paige and Knopf,[1] and described the development of the placer-mining industry at that time.

By 1909 the installation of two stamp mills and many reported discoveries of gold lodes had attracted considerable attention, and Brooks,[2] published a brief account, based on the reports of prospectors and others. F. J. Katz and Theodore Chapin, who visited the district in 1910, were the first members of the United States Geological Survey to study the gold lodes, and the results of their four days' visit were

[1] Paige, Sidney, and Knopf, Adolph, Reconnaissance in the Matanuska and Talkeetna basins, with notes on the placers of the adjacent region: U. S. Geol. Survey Bull. 314, pp. 116-118, 1907; also, Geologic reconnaissance in the Matanuska and Talkeetna basins, Alaska: U. S. Geol. Survey Bull. 327, pp. 65-67, 1907.

[2] Brooks, A. H., The mining industry in 1909: U. S. Geol. Survey Bull. 442, pp. 35-36, 1910.

published in 1911.[1] Short accounts of the developments in this mining district in 1911 and 1912 were published by Brooks, who visited a part of the district in 1912.[2]

GOLD PLACERS.

HISTORY.

Gold placer mining in the Willow Creek district began with the staking of the first claims on Willow Creek in 1897. From that time until 1899 pick and shovel mining only was carried on, but some fairly good ground was opened up, and this encouraged vigorous prospecting throughout the adjacent territory. At that time, however, placer ground was not considered sufficiently rich to justify mining unless it could be made to yield approximately $10 a day for each man. Many places were found on Willow Creek, both above and below the Discovery claims, and on its tributaries, where moderate amounts of gold could be recovered, but none of them, except the original claims and a few adjoining claims on Grubstake Creek, have proved rich enough to justify mining under present conditions. The greatest activity in placer mining was reached in 1904 and 1905, when a single hydraulic plant was successfully operated. Since 1905 activity has waned, partly on account of disputes as to the title to the ground, but principally on account of the exhaustion of the richest claims. With cheaper transportation, proper equipment, and careful management, some of the lower grade gravels could without doubt be profitably exploited.

GRUBSTAKE GULCH.

Practically all the placer gold that has been recovered from this district has been mined on Grubstake Gulch and on Willow Creek near the mouth of Grubstake Gulch. According to O. G. Herning, the first two claims were staked in 1897 by W. J. Morris and L. H. Herndon on Willow Creek at the mouth of Grubstake. In 1899 A. Gilbert staked two claims on lower Grubstake Gulch. In 1900 the Klondike & Boston Co. bought the claims on Grubstake and a number on Willow Creek, and for a number of years attempted to mine this ground. More than 6,000 feet of steel pipe, ranging from 9 to 24 inches in diameter, was placed on the ground and hydraulic methods were used. The most productive years for this company were 1904 and 1905. The company later became involved in financial difficulties and failed, and in 1908 its ground was relocated by O. G. Herning, who how holds 33 claims on Grubstake and Willow creeks.

[1] Katz, A. J., A reconnaissance of the Willow Creek gold region: U. S. Geol. Survey Bull. 480, pp. 139–152, 1911.

[2] Brooks, A. H., The mining industry in 1911: U. S. Geol. Survey Bull. 520, pp. 28–29, 1912; also, The [illegible]ng industry in 1912: U. S. Geol. Survey Bull. 542, p. 39, 1913.

Grubstake Gulch, which enters Willow Creek from the southeast, is a hanging valley, glacial erosion having lowered the Willow Creek valley below the level of this tributary. A lateral moraine of the Willow Creek glacier was built across the mouth of Grubstake Gulch, and the stream has now cut through this material and has developed a steep, narrow canyon in bedrock beneath it. From the forks of the stream to the canyon, a distance of a little more than one-half mile, the stream falls about 200 feet. Through the canyon it drops about 150 feet within a short distance. Below the canyon an alluvial fan has been built out on the Willow Creek flat, and the stream is now somewhat intrenched into the alluvial fan.

The placer ground that has been worked includes part of the bars of Willow Creek below the mouth of Grubstake, a part of the alluvial fan of Grubstake Creek, the bed of the canyon, and the bars of Grubstake Creek for some distance above the canyon. The bedrock is mica schist, and the schistosity strikes across the creek and dips upstream at moderately steep angles, thus affording a rough bedrock surface admirably adapted to retain placer gold. The schist is cut in all direction by tiny stringers of quartz, and quartz veins that reach a width of 3 or 4 feet were seen at several places within the schist area.

The first placer production was made in 1898, the gold being recovered from the claims on Willow Creek at the mouth of Grubstake Gulch. It is reported that about $4,000 was taken out that year. In 1899 about $3,000 was recovered from above the canyon on Grubstake Gulch, and a small production was made from Willow Creek. During the next four years little active mining was done, but in 1904 and 1905, when the hydraulic plant had been installed, the production reached its maximum. For the last few years mining has been carried on in a desultory manner, and the production has been small. From what could be learned at the time of the writer's visit the largest area of ground mined lies immediately above the canyon, where, throughout the length of one claim, ground averaging about 200 feet wide has been worked out. The gravels averaged 2½ to 9 feet in depth. On the lower half of the claim the gold was recovered from the surface of a bed of clay about 1 foot above bedrock, but on the upper half of the claim the gold lay on the steeply dipping schist bedrock or in the cracks in it. About 1,200 feet of sluice boxes, 27 inches wide and 30 inches deep, built of 1½-inch lumber with 3-inch square frames, were set on a grade of 6 inches to the box length, the average grade of the bedrock. Water for hydraulic sluicing is brought from a dam at the forks of the creek through a ditch and steel pipe. The pipe is 24 inches in diameter at the intake but is reduced to 9 inches at the giant, and 3 and 4 inch nozzles are used. The head of water decreased as mining progressed upstream, but was 180 feet about half a mile below the dam. It is reported that

the creek bed has been worked as far upstream as the dam. The gold is fairly coarse, and the largest nugget had a value of $14. A number of $5 nuggets were found, and pieces worth 50 cents to $1 were numerous. The gold is said to assay about $16.60 an ounce.

At the time of the writer's visit, late in August, 1913, assessment work on these claims had just begun. A giant was set about 1,300 feet above the canyon, and a cut was started to prospect the thick deposit of gravels on the east side of the creek. The gravels were there from 8 to 15 feet deep and thickened to the east, and the bedrock surface seemed to dip in that direction. Few large bowlders were found, and scarcely any rocks were uncovered which two men could not handle. The rocks were for the most part flat or somewhat rounded slabs of schist which did not move freely before the giant, and it was frequently necessary to remove them by hand, the larger ones being first broken with a hammer. Boxes 20 inches wide were in use, and two men were mining. It is reported that a good pay streak was discovered east of the present channel of the creek. The total placer production from Grubstake and Willow creeks is said to have been about $25,000.

The task of determining the bedrock source from which the Grubstake Creek placers have been derived presents some difficulties. Veins rich in free gold cut the quartz diorite on Craigie and upper Willow creeks and at once suggest themselves as an adequate source for the placer gold along Willow Creek. Upper Grubstake Gulch, however, lies entirely within an area of mica schist, and the richest placers are localized in this basin. It is therefore apparent that the placer gold above the Grubstake Canyon must have come from the schists, probably from the veins and veinlets of quartz, which are known to carry some gold. Below the mouth of Grubstake Gulch some gold from this gulch is unquestionably included in the gravels of Willow Creek. Placer prospects have been found on Willow Creek above Grubstake Gulch, and their gold was probably derived in part from veins both in the quartz diorite and in the schist. The absence of placers immediately below the outcroppings of the rich gold quartz veins in the quartz diorite is to be explained as the result of severe erosion by glacial ice, which removed any accumulations of gravel and the included gold and incorporated it in the glacial materials deposited farther downstream. The present placers are the result of postglacial concentration of gold from the glacial deposits and from the postglacial erosion of bedrock.

WILLOW CREEK.

Prospecting has been carried on at different places along Willow Creek since the first placer discoveries in 1897, but so far the only ground mined on this stream has been that just below the mouth of

Grubstake Gulch, already mentioned. The Alaska Hoosier Co. holds 32 claims on Willow Creek below the mouth of Wet Gulch, extending 2 miles downstream (see fig. 3, p. 51), but only assessment work has been done on them. Some years ago a ditch was built from Wet Gulch down the south side of Willow Creek valley for the purpose of hydraulicking some terrace gravels, but no considerable amount of mining was done. The ground has been prospected by pits and by means of a spring-pole drill. Holes have been sunk to a depth of 22 feet, but none in the valley floor have reached bedrock.

FISHHOOK CREEK.

In 1906 some prospecting for placer ground was done on lower Fishhook Creek. Encouraging prospects were found in many places, and the creek was diverted, at a point about half a mile above its mouth, into Little Susitna River. A 12-foot pit sunk into the channel showed fair returns, but no ground sufficiently rich to pay. The best prospects were found in the creek bed, and the gold decreased with depth. Bedrock was not reached. A 12-cent nugget was the largest found, and all the gold was fairly coarse, but large bowlders were so abundant that under the conditions which then prevailed the cost of mining would have been prohibitive. The placer gold along Fishhook Creek and Little Susitna River is doubtless a postglacial concentration of gold scattered through the morainal deposits, but the large number of great bowlders along these streams make it improbable that placer mining on them would pay.

GOLD LODES.

GENERAL FEATURES.

The present economic importance of this district is due in large measure to the deposits of gold quartz found in it. The important gold lode mines and prospects are described individually in the following pages, but a statement of the general conditions under which the lodes occur and of their geologic and structural relations seems desirable.

All the producing mines and the more promising prospects lie in the area of quartz diorite bordered on the south by Willow and Hatcher creeks and the east-west portion of Fishhook Creek, and on the east by Reed Creek and Little Susitna River above Fishhook Creek. Most of them are included in an area 6 miles long in an east-west direction and 5 miles from north to south. Within the narrow limits of this productive area the quartz diorite is for the most part massive and unaltered, though locally there is evidence of some shearing and its resulting alteration, and a few prospects lie within the somewhat gneissic phase of the granitic intrusion. Some claims

have also been staked in the gneisses south and east of Government Peak, but these have not yet proved to be of economic importance.

Nearly all the mines and prospects are located high up on the mountain sides or near the ridge tops, probably because the mountain tops contain large exposures of bedrock and are free from deposits of glacial material rather than because of the absence of ore bodies at lower elevations. Any veins in the cliffs and crags of the high mountains are comparatively free from cover and are much more likely to attract the attention of the prospector than those whose surface outcrops are covered by moraine, talus, or vegetation. It is not unlikely that there are valuable veins in easily accessible localities in the valleys which may long remain undetected.

CHARACTER OF VEINS.

So far as determined in this investigation the gold-bearing lodes are without exception quartz veins which cut the quartz diorite. As shown in figure 4 the veins, when plotted for strike, are divided into two main groups, one striking in a northwest direction and the other in a northeast direction. Two veins that strike approximately east were observed. At any locality veins of only one of the two main groups occur, and the two groups are therefore not intersecting veins. In the direction of the dip the veins show a marked uniformity. Except the two which strike east and west, all but two dip to the west, the average angle being 39°. In places two or even three veins in the same mountain parallel one another though separated by distances of hundreds of feet.

The veins are fillings of sharp, clean fissures in the quartz diorite. The rock is everywhere cut by several sets of prominent joints, and in every mine or prospect where the direction of jointing could be determined the veins lie parallel to a set of persistent joints and other intersecting sets cut the veins in different directions. The veins in any particular locality are more or less parallel to one another and to one set of joints, there being no quartz veins similarly related to the other joint planes. It seems certain that at the time the veins were deposited only a few of the present lines of fracture had formed, for solutions circulating through any of the openings under present conditions would have had free access to the other cracks of the same set and to the joints of other intersecting sets as well. Because of its homogeneous character the rock mass seems to offer similar conditions in all the passages, and possible precipitating solutions would also have circulated freely through all the openings that then existed. It is also difficult to conceive how the fissures could have been opened to receive their vein material without the joints having also been opened if the joints were in existence at the time the vein filling was introduced into the fissures. The noticeable restriction of the quartz

fillings to a few widely spaced fissures of a single set seems therefore to indicate that the veins were filled at an early stage in the history of the granitic mass before much of the present jointing and that after the circulation of the mineralized quartz-bearing solutions through the fissures had ceased joints were formed, some parallel to the earlier fissures and others at divergent angles. These later openings contain no veins, but only careful prospecting can show which of the openings contain veins and which are barren. When once a

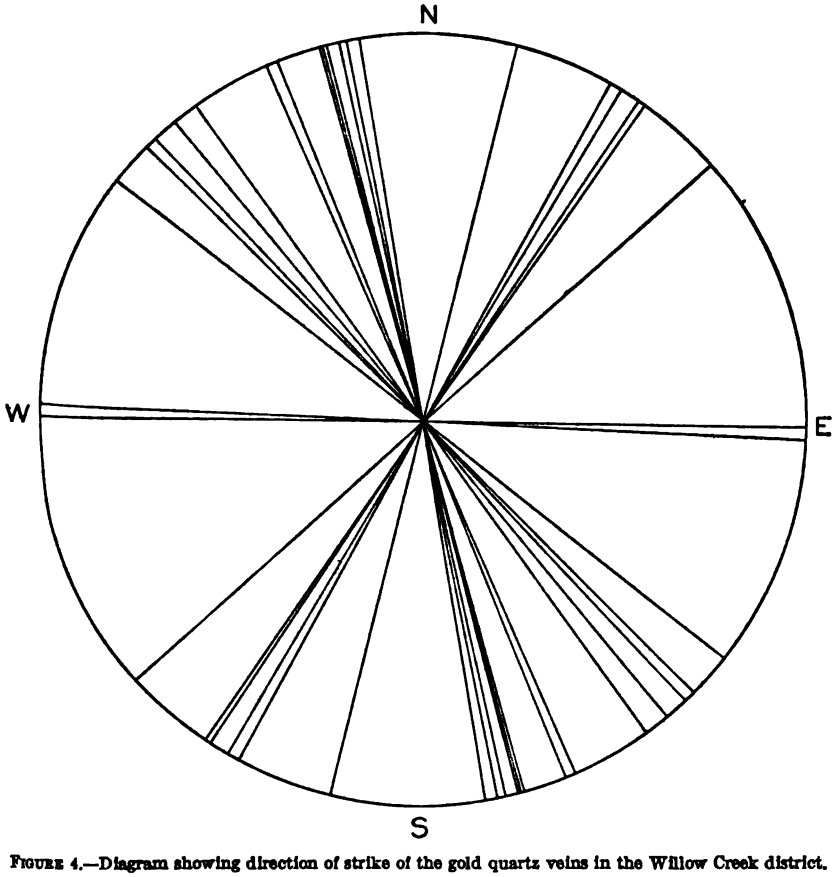


FIGURE 4.—Diagram showing direction of strike of the gold quartz veins in the Willow Creek district.

vein is discovered in any locality, however, prospecting on parallel openings seems to offer the greatest probability of success. It is believed that after the intrusion of the quartz diorite, at a considerable distance below the surface, the intrusive mass solidified and in response to stresses set up in it fissures were formed. At a time when only a few parallel fissures had developed hot aqueous solutions bearing quartz and gold and other metals circulated through the openings and deposited minerals along the passages through which the solutions were moving and fissure veins were formed.

The vein filling was distributed through a considerable period of time, during which some of the openings were filled and reopened a number of times, giving the veins a banded appearance. The gold content of the vein-depositing solutions was not everywhere and at all times the same but differed at different times and in different places. The resulting ores are therefore not of uniform value, but the richer shoots are confined to small areas within a given vein both along the strike and dip as well as to definite portions of the thickness of the vein.

Since the vein filling was completed, some movements within the rock mass have resulted in shearing and faulting. The movement has taken place along the later joints and the quartz-filled fissures and is attested by the development of slickensides on both the ore and the wall rock and by the presence of gouge along many of the veins. Some faults also cut the veins. In most places they are of small displacement and do not present serious difficulties in following the ore bodies. In one prospect, however, faulting has been more extensive, and the vein, which is cut off by a fault, had not been recovered at the time of visit.

At present too little work has been done in the district to determine definitely the extent of the ore bodies, either in length or depth. Developments show rather conclusively that one vein is continuous horizontally for a distance of 1,500 feet and another appears to be continuous for an even greater length, but on neither of these properties have underground workings actually opened ore throughout these distances. One tunnel has been driven 386 feet and another 240 feet on fairly continuous veins and veins have been shown to extend to a depth of 200 or 300 feet below the outcrop.

As the veins are fillings of clean fissures, the quartz commonly has well-defined regular walls. The ore, as a rule, breaks free from the walls, from which it is commonly separated by a layer of clayey gouge. Some veins show brecciated wall rock cemented by quartz, and horses of country rock surrounded by a quartz filling are not uncommon. The veins differ in thickness from place to place and are characterized by pinches and swells. The quartz is white to bluish gray, locally mottled with dark blue-gray patches, and in many places is banded. Near the surface croppings of the veins the ore is generally oxidized, and the visible metallic minerals consist chiefly of native gold and limonite. The oxidized ore is commonly full of cavities formed by the leaching out of the sulphides, and delicate crystals of gold extend into the cavities, showing that the gold was originally intergrown with pyrite. Oxidation, however, is confined to a shallow surface zone only a few feet in depth, and a short distance below the surface croppings the ore is unoxidized, and sulphides,

particularly pyrite, are common. Along cracks and fissures in the ore oxidation extends to greater depth than in the solid ore.

The gold occurs for the most part free, some of it surrounded by quartz and free from pyrite but much of it adjoining or intergrown with pyrite crystals. Reports of gold tellurides from this camp have been common, but chemical analyses of ore collected by the writer from a number of mines and prospects have failed to reveal the presence of tellurium. One sample of ore, however, said to have come from this district, showed considerable tellurium, but the particles of this telluride were too minute to be identified. Besides free gold the following metallic minerals were identified in the quartz veins of the district: Pyrite, arsenopyrite, stibnite, chalcopyrite, bornite, chalcocite (?), galena, malachite, limonite, cinnabar, and an unknown telluride. Specimens of molybdenite associated with quartz have been obtained in this district, but no molybdenite was seen in the gold-bearing quartz veins, and the specimens may have come from pegmatite veins. The malachite and limonite are plainly secondary and are oxidation products, probably of chalcopyrite and pyrite. Cinnabar was seen at only one place, where it occurs as a filling of small fractures in the quartz. It was, therefore, introduced some time after the main vein filling had been deposited.

The assemblage of original vein-forming metallic minerals listed above seems to be characteristic of gold-bearing veins of deep-seated origin, deposited by aqueous solutions. Lindgren [1] includes gold, pyrite, chalcopyrite, arsenopyrite, galena, molybdenite, and tellurides as characteristic of veins formed under these conditions. Under Emmons's [2] classification also this assemblage could be found in veins deposited under deep-seated or moderately deep seated conditions. Most of the minerals listed are, however, not clearly diagnostic, as they may have a wide vertical range. The evidence produced by the underground workings in this camp is as yet too meager to serve as the basis for a final statement of the conditions under which the ore was deposited.

The evidence gathered in this district seems to indicate that the gold now present in the ore bodies which are being mined was originally deposited at the same time as the inclosing quartz and that there has since been no removal of gold by solution from the veins or addition of gold to them. In other words, the amount of gold in a given volume of any vein is the same now as at the time the quartz filling was completed. Oxidation has affected only a very shallow surficial portion of the veins, and in the oxidized portions only the

[1] Lindgren, Waldemar, The relation of ore deposition to physical conditions: Econ. Geology, vol. 2, pp. 105-127, 1907.

[2] Emmons, W. H., A genetic classification of minerals: Econ. Geology, vol. 3, pp. 611-627, 1908.

relatively soluble sulphides have been removed, and the gold, which is soluble with difficulty, has been left behind. It is true that mill tests of the surface portions of the veins often show larger content to the ton than is recovered from deeper portions of the same veins, but this is in part due to the fact that after the sulphides have been removed the specific gravity of the ore is reduced, and a larger volume of vein matter with its included gold is required to make a ton. Then also some residual gold from the eroded vein outcrops may find its way into the ore and thus the recovery is in excess of the true gold content of the original vein material. The mill concentrates from unoxidized ore carry considerable gold, probably in the form of free gold intergrown with pyrite. In the oxidized ore this gold has been freed by the removal of the pyrite and is recovered by amalgamation. Thus several factors tend to give a greater recovery of free milling gold from the surface portions of the veins than from the deeper unoxidized portions. Assay tests, however, which determine the gold content irrespective of the presence of sulphides, seem to show that in general the surface oxidized ores are no richer for the same volume than the deeper unoxidized ores. It can therefore be stated with much confidence that secondary enrichment of the ores by the solution and redeposition of gold has played no important part in the concentration of gold within the veins, and ores equally rich as those now mined at shallow depths probably extend as far downward as the cost of mining will permit the veins to be exploited.

MINE OF ALASKA FREE GOLD MINING CO.

The property of the Alaska Free Gold Mining Co. comprises a group of 13 claims lying on the bold mountain ridge which forms the west wall of the Fishhook Creek valley, north of Hatcher Creek (Pl. II, in pocket). The claims, which cover practically all the east slope of this ridge and include a part of the west slope near the summit, have been surveyed for patent, as has also a mill site on Fishhook Creek. The arrangement of the claims is shown on figure 5.

The company is organized as a stock company, but is now operated under an eight-year lease which began in 1912. It was on this property that the first discovery of gold quartz in this district was made in 1906. Since that time development work and mining have been carried on each summer. The improvements at the mine consisted at the time of the writer's visit of two inclined tunnels 50 and 85 feet long on the lower vein connected by drifts and stopes; a 95-foot adit tunnel on the main upper vein; numerous short tunnels, open cuts, and pits on the vein croppings on the different claims; a mill and blacksmith shop on Fishhook Creek and adjoining bunk and mess tents to accommodate about 30 men; and two main tramways and a branch tram which connect the mill with the ore bodies.

The Lane slow-speed Chilean mill (Pl. XIII, *B*), which is operated by a Pelton wheel working under a 35-foot head of water, is designed to turn about seven revolutions a minute and to crush to sizes from 40 to 60 mesh. It was first put in service about August 1, 1912. Its

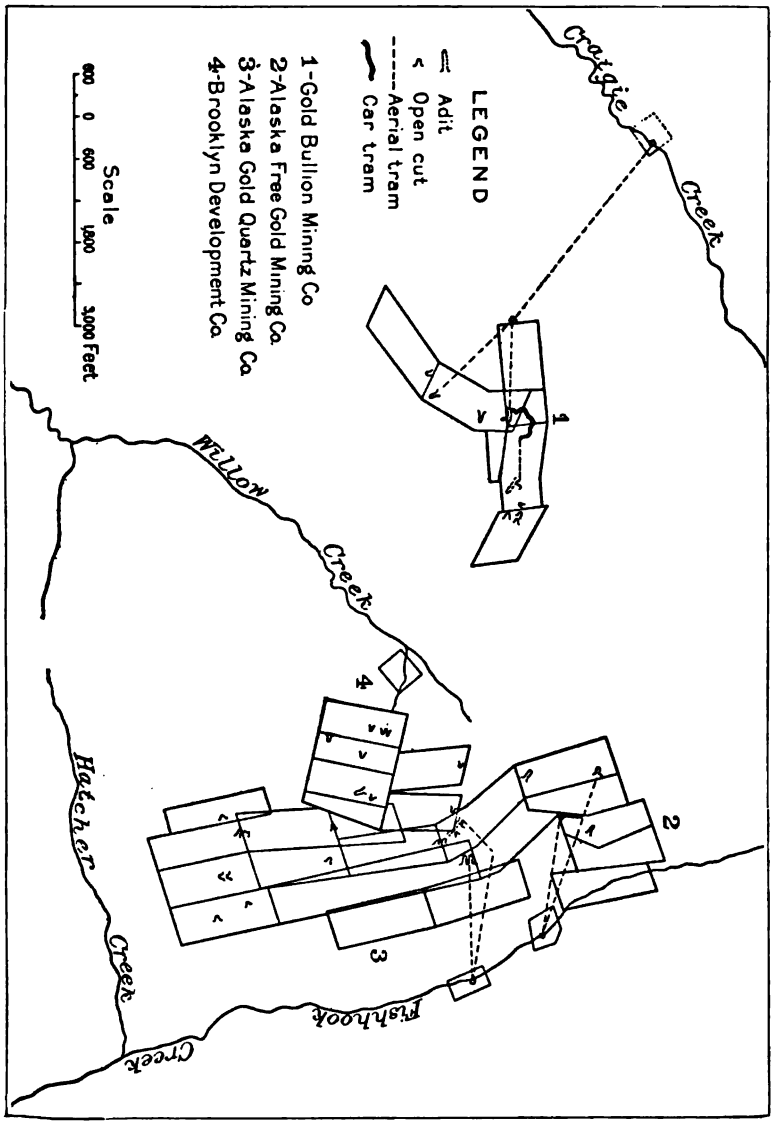


FIGURE 5.—Sketch map showing four groups of claims in Willow Creek district, surveyed by C. S. Hubbell and H. H. Waller.

maximum capacity is about 25 tons each 24 hours. The ore is passed through a rock crusher before entering the mill. The water supply is adequate to operate the mill during only part of the open season, and a 16-horsepower gasoline auxiliary engine has been installed to furnish power during periods of low water. From the mill the

crushed ore passes to two sets of amalgamating plates and thence is fed to two Bartlett concentrating tables, operated by a small overshot water wheel. From 1 to 2 per cent of the ore crushed is saved as concentrates. From 70 to 75 per cent of the gold saved is said to be amalgamated in the mill, and the remainder is caught on the plates. At present the concentrates and tailings are not treated but are stored until the time when a cyanide plant is installed.[1]

Two principal ore bodies have been opened on this property, although there are openings at a number of places on veins which may or may not be continuations of these two main veins. The lower of the two veins has been opened at the head of the south tramway, at an elevation of about 4,300 feet, 900 feet above the mill, and will here be called the Homestake vein, as the principal workings are near the boundary between the claims known as the South Homestake and North Homestake. This vein outcrops at about the same elevation and has the same general strike and dip as the Granite Mountain vein of the Alaska Gold Quartz Mining Co., 1,500 feet to the north. It appears likely that the vein is more or less continuous between these two properties, although it has not yet been directly traced throughout the intervening distance. At the head of the tramway the vein is opened by two inclined tunnels 50 feet apart, one 85 and the other 50 feet long, connected at 50 feet from the surface by a drift. The ore was brought to the surface in a car tram operated by windlass. Most of the ground between these tunnels is stoped out for 25 feet below the outcrop. The average strike of the vein is here about N. 13° W., and the dip ranges from 30° W. at the surface to 42° W. at the tunnel face. The vein filling, which lies between quartz diorite walls, was 6 to 24 inches thick and was associated with some gouge and clayey matter. The vein cropping has been exposed for several hundred feet along the surface. To the north it has been traced as far as the north tramway and to the south it was followed to the edge of a large talus slide. It is said that it pinches out to a thin edge to the south. In 1912 a large part of the ore milled at this mine is said to have been taken from this vein. Several hundred tons of ore were treated, the gold recovered running from $15 to $30 a ton and averaging about $20 a ton.

The upper main vein on this property, known as the Skyscraper vein, is opened by a tunnel at an elevation of 4,580 feet on the north slope of Skyscraper Mountain, near its top (Pl. XIII, *A*). These workings are at the head of an 850-foot branch of the aerial tram, which runs in a northeast direction and discharges at the head of the main north tram, 2,500 feet from the mill. At the time of the writer's visit the adit tunnel, which is equipped with a car tram, was 95 feet long and work was in progress in the breast. At 40 feet from

[1] Another mill and a cyanide plant were added to the equipment in the fall of 1914.

A. SKYSCRAPER MOUNTAIN FROM THE NORTH.

A conspicuous set of westward-dipping joints may be seen. The Skyscraper vein of the Alaska Free Gold Mining Co. lies along one of these joints. The tunnel mouth may be faintly seen below and to the left of the peak.

B. MILL OF ALASKA FREE GOLD MINING CO. ON FISHHOOK CREEK.

A. GRANITE MOUNTAIN, WITH THE MILL AND WORKINGS OF THE ALASKA GOLD QUARTZ MINING CO.

B. MILL OF ALASKA GOLD QUARTZ MINING CO. ON FISHHOOK CREEK.

the portal a raise reaches the surface 36 feet above. As opened by this tunnel, the vein ranges in thickness from 18 inches to 8 feet of solid quartz, associated with some gouge. The vein matter is generally free from the walls, and there is evidence that considerable movement has taken place along the walls. The vein pinches and swells, but the strike and dip are fairly uniform. The average strike is about N. 15° W. and the dip from 40° to 45° W.

A short distance southeast of the tunnel and above it, on the outcrop of the same vein, is a large open cut which supplied about two-thirds of the ore milled in 1913. In this cut the vein is split into two parts by a large horse of diorite 15 feet in thickness. Above the horse is said to be about 5 feet of milling ore and below it from 4 to 10 feet of ore. At a point 380 feet southeast of the mouth of the tunnel is another open cut on the same vein, showing about 9 inches of quartz. The tunnel is being driven toward this point.

The quartz of the Skyscraper vein is in general massive, although it locally shows a banded structure. In the open cuts it is rusty from iron oxide and full of cavities formed by the leaching out of the sulphides. A short distance from the surface, however, the sulphides have been oxidized only along cracks in the vein, and the massive quartz is light to dark blue-gray. It contains, besides native gold, rather abundant pale pyrite, some chalcopyrite, and a little galena. In places the cracks in the vein quartz and in the inclosing quartz diorite are filled with incrustations of epsomite or Epsom salt, a hydrous magnesium sulphate. The native gold occurs both as particles in the quartz not immediately associated with pyrite and also as intergrowths in the pyrite, as can be seen from the delicate crystals projecting into the cubical cavities from which the pyrite has been leached.

A third vein of proved economic importance outcrops on the Eldorado claim, about 3,000 feet south of Skyscraper Mountain. This vein has been developed by several large open cuts and by a 30-foot inclined tunnel, at an elevation of about 4,270 feet. The country rock is a much decayed quartz diorite. The vein ranges in thickness from 1 inch to 18 inches of solid quartz, associated with some clayey gouge. It strikes N. 24° W. and dips about 36° W. and is therefore nearly parallel with the other veins on Skyscraper and Granite mountains to the north. The quartz is oxidized and rusty, as is also the country rock, even at a distance of 30 feet from the surface. It is reported that in 1912 about 100 tons of ore from this vein was dragged down a trail to a point from which it could be trammed to the mill.

A number of other open cuts and short tunnels on this property expose quartz veins of different sizes and gold content, but none of them has yielded ore in commercial quantity.

In 1911 a few tons of ore from this property was milled in the mill of the Alaska Gold Quartz Mining Co., and yielded the first gold produced from this mine. In the spring of 1912 the Chilean mill was installed. In 1913 the mill was run to as great capacity as the water supply permitted and about 25 men were continuously employed during the working season.

MINE OF ALASKA GOLD QUARTZ MINING CO.[1]

The property of the Alaska Gold Quartz Mining Co. lies for the most part in the upper portion of the valley of Fishhook Creek, on the east slope of Granite Mountain (Pl. XIV, *A*). It comprises a group of five claims and a mill site, all of which have been surveyed for patent. The claims form an irregular tier extending from Fishhook Creek up the mountain to the west and include a portion of the divide between Fishhook Creek and the head of Willow Creek. The position and arrangement of the claims are shown on figure 5 (p. 61). The claims were located in 1907, and development work and mining have been carried on each year since. The improvements consist of a 4-stamp mill,[2] located on Fishhook Creek (Pl. XIV, *B*), two aerial tramways extending from the ore bodies to the mill, a group of tents in the valley, a blacksmith shop and car tram at the main tunnel, several hundred feet of adit tunnels and stopes, and a number of open cuts on the croppings of the ore bodies. The mill is operated by a small Pelton wheel, which works under a 120-foot head and develops about 15 horsepower. The mill equipment first installed consisted of a prospecting mill of three 500-pound stamps, manufactured by the Mine & Smelter Supply Co. Later a 1,250-pound Nissen stamp was added. The capacity of the four stamps was about 8½ tons in 24 hours with the small stamps dropping 98 times per minute and the large stamp 90 times. The ore is crushed to 40 mesh and passes from the stamps over amalgamating plates, and thence over a Wilfley concentrating table. The concentrates are said to bear a proportion of about 1 to 80 in the more or less oxidized portions of the vein and of about 1 to 40 in the unoxidized ore about 400 feet from the surface. The concentrates and tailings have been saved for future treatment, but so far all the production has been in free gold obtained by amalgamation in the mortars and on the plates. When the mill is running to capacity the plates are cleaned every 24 hours and the mortars once a week. Two 2-bucket aerial trams equipped with ⅝-inch cable lead from the ore bodies to the mill. The lower of the two, heading at the mouth of the main tunnel, is about 1,700 feet long and is supported by one tower near the mill. The other

[1] This property was taken over by the Independence Gold Mining Co. in 1914.
[2] This plant was enlarged in 1914.

tram is 2,460 feet long in a single span and has a vertical distance of about 1,100 feet between the ends.

Two principal ore bodies outcrop on this property. The main tunnel on the lower or Granite Mountain vein, which has furnished most of the production and which outcrops on the walls of a small cirque (Pl. XIV, *A*), is at an elevation of about 4,150 feet, or 500 feet above the mill. The upper or Independence vein lies high on the mountain, 620 feet vertically above the Granite Mountain vein, and at the time of visit had been prospected only by shallow openings. The country rock is everywhere the quartz diorite, which covers all the northern part of this district.

The Granite Mountain vein is developed by a main tunnel 386 feet long (Pl. XII, *B*), another tunnel 80 feet long, several short tunnels and open cuts, and several stopes, some of which connect the two larger tunnels with each other and with the surface. In general, the vein strikes N. 14°–20° W., the strike differing somewhat in different parts of the vein. The dip also is rather irregular, ranging from 10° to 42° SW., but averages about 20° SW. At the portal of the main tunnel the vein cropping shows only an inch or two of quartz, but in the tunnel the quartz vein matter ranges in thickness from 2 inches to 4 feet, rarely pinching to less than 8 inches and averaging about 22 inches. The vein pinches and swells abruptly and contains some horses of country rock, but is continuous throughout the tunnel. In one place a dip fault has displaced the vein about 4 feet.

The vein walls are distinct and smooth, are generally slickensided, and are in most places separated from the vein by a layer of gouge matter a few inches in thickness. The quartz is characteristically massive, though it is banded in places; it is light gray to dark blue-gray, and where unoxidized shows, besides native gold, rather abundant pale pyrite, some chalcopyrite, and specks of some unidentified dark sulphide. The vein matter has been somewhat shattered and slickensided. Very near the surface the ore is rusty and most of the sulphides have been removed by oxidation. Farther underground iron oxide occurs along certain cracks in the ore, but most of the sulphides are unaltered a short distance from the surface. The better ore from this vein occurs in shoots, four of which were encountered in a distance of 386 feet along the strike of the vein. In general, an attempt has been made to keep the value of the ore milled up to at least $30 a ton, and the boundaries of the shoots as mined are therefore at about the point where the value falls below this figure.

The upper vein on this property is known as the Independence vein and is connected with the mill by an aerial tram at an elevation of 4,770 feet or 1,120 feet above the mill. The vein strikes N. 12° W., or approximately parallel to the Granite Mountain vein, and its

average dip is about 42° W. Although its southward continuation has not been directly proved, it is without much doubt on the same plane as the Skyscraper vein on the property of the Alaska Free Gold Mining Co., and future developments are likely to show that the vein is continuous between these two properties. The developments at the time of the writer's visit consisted of an open cut about 100 feet long and a 15-foot tunnel at the head of the tramway and other open cuts on the vein both to the north and to the south. The vein, as seen at the several openings, is 2 inches to 2 feet in thickness, averaging about 12 inches, and is accompanied by considerable sheared matter and gouge. The walls consist of blue-gray quartz diorite, somewhat sheared near the vein. The vein near the tramway is forked, a portion of it cropping out about 30 feet below the tunnel. The vein quartz is less massive than that of the Granite Mountain vein, is generally banded, and consists of interlocking crystals of quartz containing free gold, a little pyrite, and small quantities of some other sulphides. Only a small quantity of ore from this vein had been mined up to the fall of 1913, but is was planned to build a cabin near the outcrop and run a tunnel on the vein that fall. It was reported that on September 3, 1913, this tunnel had been driven 34 feet on the vein and that approximately 4 feet of good ore showed in the tunnel face.

MINE OF GOLD BULLION MINING CO.

The Gold Bullion Mining Co.'s property is situated on the southeast wall of Craigie Creek valley, about 4 miles above the mouth of the creek. The first claims were staked in 1907 by William Bartholf, and the group now includes five full claims and a fractional claim, which have been surveyed for patent. The arrangement and position of the claims are shown on figure 5 (p. 61). The improvements consist of a group of buildings and a 7-stamp mill located in the valley (Pl. XV), two branch aerial trams supplying a main aerial tram to the mill, a short aerial tram and a car tram at the upper workings, which are provided with a stone mess house, blacksmith shop, and bunk tents, several hundred feet of tunnels and stopes, and numerous open cuts and strippings.[1] The main workings are connected with one another and with the mill by trails. Power for the mill is provided by a 12-inch Pelton wheel operated under a 28-foot head, about 25 horsepower being developed. Some power is also used to run the main tramway. Two 1,000-pound Hendy stamps were installed in 1909, and in 1911 five 1,000-pound Halladie stamps were added. The ore is first passed through a coarse crusher and then fed to the stamps, which are regulated to drop from 100 to 103 times a minute, crush to 40 mesh, and discharge over two sets

[1] A cyanide plant having a capacity of 45 tons daily was added in 1914.

MILL AND CAMP OF GOLD BULLION MINING CO.

The veins outcrop near the top of the mountains in the background. The impounded tailings may be seen below the mill.

of amalgamating plates, and thence over a Wilfley concentrator. The capacity of the stamps is about 21 tons of ore in three shifts of eight hours each, and the ore concentrates in about the ratio of 1 to 200. In 1909 the two stamps then installed were supplied with ore brought to the mill on pack horses, but the next year a cable tram was installed. The main tramway which now supplies the mill is a 2-bucket aerial tram, equipped with ⅞-inch cable, and is 3,253 feet long, with a rise of 850 feet. It is supported on a number of towers. The buckets have a capacity of 400 pounds, and the tram is of sufficient capacity to keep the mill well supplied with ore. At the head of the main tram there are ore bunkers supplied by two trams, one about 1,600 feet long from tunnel No. 5 and one 1,450 feet long from tunnel No. 2, each equipped with ¾-inch cable and two buckets. These trams consist of single spans unsupported by towers. From the mouth of tunnel No. 2 a car tram 945 feet long follows the mountain slope to the northeast and is fed by an aerial tram 635 feet long, which heads at Discovery, on the Gold Dust claim.

The vein croppings on the Gold Bullion property occur near the summit of the ridge which separates the upper valleys of Craigie and Willow creeks. The workings are at elevations of 4,400 to 4,600 feet, and the mill in the valley bottom is 3,050 feet, or about 1,500 feet below the ore bodies. The discovery of the veins on this property in the high, craggy ridge top is, no doubt, due to the good exposures of bedrock which occur there. Below the workings most of the bedrock is so concealed beneath a covering of talus and of glacial deposits that prospecting is difficult.

The ore milled in 1909, which yielded the first gold recovered from this property, is said to have been obtained from the talus and from open cuts on the Gold Dust claim, the place of the original discovery. From 1910 to 1912 the ore milled was taken from tunnels Nos. 3, 4, and 5, No. 5 furnishing most of the production. In 1913 the production was largely obtained from open cuts and from tunnel No. 1 on the Gold Dust claim, from the same locality that was first mined.

At the time of the writer's visit access could be had to the many open cuts on the property and to adit tunnels Nos. 1, 2, and 4. Tunnels Nos. 3 and 5 had caved at the portals and were inaccessible. Active mining was in progress in open cuts near tunnel No. 1 and in that tunnel itself, which was 30 feet long, and a prospecting tunnel, No. 2, was being driven along the vein and had penetrated several hundred feet into the mountain. Between these two tunnels numerous open cuts and strippings have exposed the vein, and, although the exposures are not continuous, it is most likely that both tunnels, and No. 3 as well, are all on the same vein. Tunnels Nos. 4 and 5, though somewhat higher on the mountain than the projected dip of the vein from No. 2 would indicate, are in ground that has been

somewhat faulted and disturbed, and it is not improbable that the veins on which they were driven are parts of the same ore body exposed in the other workings. The vein may, however, be somewhat displaced by faulting, or it may even prove to be a distinct ore body.

At tunnel No. 1 the vein strikes about N. 28° E. and dips 15° W. Open cuts show its continuation on the opposite side of the ridge to the south. At the time of the writer's visit the tunnel was 30 feet long, but it is reported that by October 15, 1913, it had been driven 184 feet. As exposed in the tunnel the vein is 3 to 7 feet thick and is composed largely of white or bluish quartz, rusty along the fractures. Sheared matter and gouge occur both above and below the vein, which cuts the quartz diorite. Many pieces of the ore contain visible particles of free gold, as well as small amounts of pyrite and chalcopyrite. Particles of some other finely disseminated sulphides are also present, and copper carbonate stains are common. Although both the country rock and the vein are much fractured, many of the fractures being filled with ice, the ore at even so short a distance as 30 feet from the portal of the tunnel is not greatly oxidized, except along fractures, and many of the sulphides are unaltered. The open cuts at this place have disclosed a large amount of oxidized and broken vein quartz mixed with the surface detritus, and this loose surface material supplied a considerable proportion of the ore milled in 1913. The surface portion of the vein seems to yield somewhat higher returns than the fresher material from the underground workings, probably as a result of the freeing of some gold by the oxidation of the sulphides. At present the only gold recovered is free gold, obtained by amalgamation. Tunnel No. 2 has yielded a little milling ore, but most of the tunnel has been driven in the hope of opening an ore body. The mouth is on the Golden Wonder claim, and the vein, which ranges in thickness from 5 feet to the vanishing point and averages about 2 feet, strikes approximately N. 30° E. and dips about 14° W. In the breast of the tunnel the vein had thinned out to a small stringer. It is reported that on October 15, 1913, the tunnel had been driven 240 feet and the vein had increased to a width of 3½ feet of paying ore.

Tunnel No. 3, about 400 feet west of No. 2 and presumably on the same vein, is now caved, but is reported to have yielded considerable good ore.

Tunnel No. 4 is said to be 300 feet long and the vein ranges in thickness from 2 feet down to a small stringer. No work was being done in it in 1913. In one place in this tunnel cracks in the vein quartz were filled with cinnabar, which had evidently been introduced after the vein had been filled. The amount of cinnabar is small, but

the occurrence is of interest, as it is the only place in the district from which this mineral has been reported.

Tunnel No. 5, which is now caved and abandoned, furnished most of the ore milled in 1912. The vein is said to have had a maximum thickness of 14 feet, though averaging much less than that. In 1913 a small quantity of ore was recovered from the outcroppings of the vein near the site of the old tunnel entrance.

In the mill practice at this mine the only metal which has been recovered so far has been the free gold caught by amalgamation in the stamp mortar boxes and on the plates. In 1913, during the time when the mill was running 24 hours a day, the plates were cleaned up at the end of each 8-hour shift, and the mortars were cleaned every 48 hours. The concentrates from the Wilfley table have been stored separately and all the tailings have been impounded. About 4,000 tons of tailings are now stored ready for treatment, and plans are being made to install a 30-ton cyanide plant in 1914. The tailings are said to carry an average of over $16 a ton in gold. In 1913 the mill was run three 8-hour shifts a day, and two shifts were worked in the mines. About 30 men were continuously employed during the summer. In the fall the number of stamps in operation was reduced as the water supply diminished. The 5-stamp mill ran during the season for a total of 59 days and the 2-stamp mill for 72 days. It was planned to continue underground mining all winter.

MABEL MINE.

The Mabel mine is situated on the west wall of the Little Susitna Valley, 3 miles above the mouth of Fishhook Creek. The workings, at an elevation of 3,700 feet, are in a small gulch tributary to Little Susitna River, and the camp is near the same gulch, about 800 feet below the workings. The property comprises a block of 12 claims staked to cover the known outcroppings of the veins. The claims were staked in the fall of 1911, and a moderate amount of development work has been done since that time. In 1912 an open cut was made on the vein and an inclined tunnel driven down the vein for some distance, but water in this tunnel became troublesome and it was decided to drive an adit tunnel below to crosscut the vein. At the time of visit the open cut and inclined tunnel were badly caved and little could be seen, but in places a slip zone said to be on the vein and containing about 8 inches of gouge and a little quartz was observed to cut through the quartz diorite country rock. This zone strikes in a general northerly direction and dips about 45° W. The vein as opened in the inclined tunnel, is said to range from 2 to 18 inches in thickness. Ore taken from it showed a decided banding of white quartz with visible interlocking crystals and dark blue-gray fine-grained quartz.

Several tons of quartz were obtained from the workings in 1912, and 6 tons was shipped to Tacoma for smelting.

In 1913 an adit tunnel was started 20 feet below the earlier workings and when visited had been driven 51 feet under cover. It was expected that the vein would be struck within a short distance. Near the mouth of this adit tunnel another quartz vein, cutting quartz diorite, strikes N. 52° W. and dips 55° SW. It is from 6 to 8 inches thick, and consists of massive rusty and oxidized quartz which breaks free from the walls and contains some horses of country rock. The sulphides have for the most part been removed by oxidation in this surficial portion of the vein, though some pyrite remains. It is probable that the amount of sulphides will be found to increase at no great distance from the surface. Visible free gold could be seen in many specimens of the quartz, and small pieces mortared and panned gave many colors of free gold.

A good horse trail has been built from the wagon road to the camp and also to the tunnel mouth. Plans were under consideration to construct an aerial tram from the tunnel to a mill site on Little Susitna River in 1914.

ARCH PROSPECT.

The Arch prospect is situated on the south side of Archangel Creek, about 1½ miles above the mouth of that stream, at an elevation of 3,200 feet, 550 feet above the valley bottom. This property, which consists of a group of four claims called the Arch group, has been generally known as the Fern, Taulman & Goodell prospect, but changed hands in the summer of 1913. At the time of the writer's visit there was no one on the ground, and the main tunnel was caved and partly filled with water, so that little could be seen. A good stone house and blacksmith shop have been built near the prospect, and a good trail extends from the cabin to the main trail in Little Susitna Valley.

The vein, which cuts quartz diorite, has been developed by a number of open cuts and by an inclined tunnel said to be 80 feet long. The tunnel follows down the vein, which in the somewhat disturbed ground through which the outer portion of the tunnel is driven strikes N. 33° E. and dips 21° NW. In the accessible portion of the tunnel the vein was 10 to 40 inches wide, and the filling was mostly a clayey gouge, with little quartz. It is said that farther within the tunnel a maximum of 12 inches of quartz was observed. The quartz, as seen on the dump, is banded and consists of interlocking quartz crystals surrounding pieces of altered country rock. Sulphides occur only in small amounts.

Under the new management an adit tunnel to crosscut the vein 180 feet below the old incline was started in the fall of 1913, and two

other drifts are reported to have cut the vein, showing from 12 to 20 inches of quartz with an average gold content of $32 a ton. It was planned to install two small Lane mills on Archangel Creek in the summer of 1914, water for power being obtained from the tributary which joins Archangel Creek from the south near the mill site.

PROSPECT OF BROOKLYN DEVELOPMENT CO.

The Brooklyn Development Co.'s property consists of five mining claims and a mill site in the basin at the head of Willow Creek. The claims are said to have been located in 1909 and have been surveyed for patent. (See fig. 5, p. 61.) The developments consist of two buildings in the valley bottom, a large number of open cuts and trenches, and two tunnels. The upper tunnel, at an elevation of 4,400 feet, is 40 feet long, and is driven through quartz diorite. It was started on a quartz vein 6 to 8 inches thick, striking approximately east and dipping 15° S. A short distance from the entrance the vein was cut off by a fault, and the remaining portion of the adit shows little vein matter, although the diorite is seamed and fractured, and a little clayey material appears along some of the fractures. The quartz from the vein near the entrance is rusty and much fractured, and shows some banding. The vein is now for the most part concealed, but the few bits of quartz obtainable showed little mineralization.

The main adit, about 60 feet below the shorter one, is a somewhat crooked tunnel 180 feet long, and three 10-foot crosscuts extend from it to the south. On the surface there is said to have been a vein cropping of about 7 inches of quartz, but the tunnel follows a seam in the quartz diorite containing some clayey material but almost no quartz. In the breast of the tunnel there are a few small quartz stringers, and one crosscut shows 2 inches of clayey gouge with a little quartz. No ore body has been developed in this tunnel. The numerous open cuts and trenches on the property are caved and little could be seen in them.

A stamp mill for this property was purchased several years ago and freighted in to a point on Willow Creek 7 miles below the cabins, but has not been installed.

MAMMOTH PROSPECT.

A group of four claims, known as the Mammoth group, is located in the Willow Creek valley on the mountain which lies north of the pass between Fishhook and Willow creeks. The main workings lie at an elevation of 3,800 feet, or 450 feet above Willow Creek. Active development work was carried on during the winter of 1912–13, and a 200-foot tunnel, with 73 feet of crosscuts and a 12-foot raise, was driven. The vein at the tunnel entrance shows a large body of

quartz 28 to 30 feet wide, striking approximately east and dipping 68° N. About 30 feet from the tunnel entrance a fault has cut off the vein abruptly, and the remaining 170 feet of tunnel on this level was driven on a slip zone full of clayey gouge, but the vein was not again encountered. The country rock is a somewhat gneissic quartz diorite which has been broken by slips in several directions. The walls of the slip zone on which the tunnel was driven are well defined, and although they show some rolls, the direction of the zone is fairly constant. The walls are smooth and in many places show slickensides, and the rock has been much altered. In the breast there is about 3 feet of clayey gouge and sheared, altered diorite, with good walls of solid rock on either side. A 35-foot crosscut to the north leaves the main tunnel 100 feet from the portal, and one or two other short crosscuts have been made, in none of which was the vein encountered. About 70 feet from the portal a 15-foot raise on a slip zone entered a body of quartz, but a 28-foot crosscut from the raise cut through the quartz body, which proved to be an irregular portion of the vein surrounded on all sides by faults. The faulted-off portion of the main vein has not been found in the underground workings.

The quartz is for the most part massive, white, and vitreous, mottled with patches of bluish gray. It shows scattered specks of pyrite and chalcopyrite with stains of copper carbonates. The assays that have been made show the vein to consist of ore which for this district is low grade. The vein is, however, the largest seen in the region, and if its underground continuation is established, and the tenor holds, there is here the possibility of a mine from which much gold might be recovered.

MINE OF MATANUSKA GOLD MINING CO.

The property of the Matanuska Gold Mining Co. is situated on the north side of a cirque in which Fairangel Creek has its head. At the time of the writer's visit there was no one on this ground, and only assessment work has been done for the last two years, as the property is now involved in litigation. The four claims of this group were staked in 1909, and considerable development work was done in 1910 and 1911. A good trail was built from the Little Susitna Valley to the workings, many open cuts were made, and tunnels aggregating over 200 feet in length were driven. The camp, consisting of several tents, is near the creek, at an elevation of about 3,500 feet. The country rock in this vicinity is a coarse gray quartz diorite with many inclusions of a finer-grained gray sugary diorite. The diorite is cut near the vein croppings by small aplite dikes, locally called "quartzite." The dikes are older than the vein fillings, for in places the quartz veins cut the dikes, and cracks in the dikes are filled with quartz.

The working nearest camp, at an elevation of 3,680 feet, is a 20-foot tunnel in diorite. No veins show in this tunnel, which was evidently driven to crosscut a vein that crops out on the slope 50 feet above. At the cropping a 22-foot adit shows two quartz veins in the breast, one from 1 to 3 inches thick, striking N. 22° W. and dipping 42° NE., and the other from 3 to 8 inches thick, striking N. 47° E. and dipping 71° NW. Above the tunnel the smaller vein has been exposed by stripping for a vertical distance of about 50 feet. At a point about 75 feet west of this exposure an adit tunnel, which is said to be 85 feet long, has been driven to intersect the larger of these veins. A cave-in has closed this tunnel about 60 feet from the portal, but it is reported that the position of the vein is believed to be about 10 feet beyond the breast of the tunnel. The tunnel is driven on a slip zone, from 12 to 18 inches wide, which contains much gouge and a little quartz and which strikes N. 44° W. and dips 72° NW., or approximately parallel to the vein in the tunnel. The vein matter, as seen in the tunnels and on the dumps, is 3 to 12 inches thick and consists of banded white and blue-gray quartz. The quartz contains some visible particles of free gold and considerable sulphides, mostly pyrite. Near the surface it is somewhat rusty and shows small cubical cavities containing iron oxide, the result of the leaching of the pyrite. The gold content of this vein is said to be high, averaging about $100 a ton.

At an elevation of about 3,930 feet, or approximately 250 feet above the vein just described, is another quartz vein closely associated with an alaskite dike. The vein is younger than the dike, the quartz cutting across the dike and filling fractures in it. A tunnel has been driven for 84 feet along the vein, which strikes N. 33° E. and dips 45° W. The vein is distinct on the hanging wall, there being in places 12 to 15 inches of solid quartz. Below this hanging-wall quartz a stockwork of reticulated quartz veins incloses fragments of diorite and contains some gouge. At many places the walls and the ore show slickensides. The same vein is exposed a short distance above the tunnel by strippings and by an open cut. Here the dike and the vein come together. The dike, which along its outcrop ranges in thickness from 1 to 6 feet, is at the cut about 6 feet thick, and the quartz lies parallel to it both above and below. The vein pinches and swells, but in places showed 30 inches in vein matter, mostly quartz, with small inclusions of altered diorite. Some caving has taken place in this cut, and the relations have thereby been partly obscured. The vein walls, the quartz filling, and the diorite fragments inclosed in the quartz all show fine specks of sulphides, mostly pyrite.

Another 24-foot adit tunnel on this property was driven on an alaskite dike locally called "quartzite." The dike rock contains disseminated pyrite, but assays did not show sufficient gold to warrant farther exploration.

MILLER PROSPECT.

The Miller prospect is on the east side of Little Susitna River, 1 mile below the mouth of Fishhook Creek, and about 60 feet above the river. The developments consist of two cabins on the west side of the river and a 30-foot tunnel driven from the bottom of a steep, narrow gulch. The tunnel follows a thick band of siliceous rock, which has been locally called a vein but which proves from study in thin section to be an altered alaskite dike. The "ore" is white to greenish-gray in color and in places contains considerable sulphides. The so-called "vein" is ill defined in outline, and little of it is exposed. The associated rock is coarsely crystalline, and belongs to the gneiss series. Only assessment work has lately been done on this property. Nothing definite was learned of the value of the ore, as assays are said to have given conflicting returns.

MOGUL PROSPECT.

The Mogul prospect comprises two claims situated on a high rock bench in upper Reed Creek valley, 2½ miles above the mouth of that stream, at an elevation of about 4,000 feet. The claims were staked in September, 1912, and have been developed by three open cuts about 15 feet from one another along the croppings of a quartz vein that cuts quartz diorite. The southernmost cut, about 10 feet long on the bottom, shows about 6 inches of clayey gouge with 2 inches of quartz. The middle cut shows 19 inches of clayey vein matter with 1 to 4 inches of quartz. The north cut shows 4 inches of quartz and gouge above, separated by 18 inches of altered diorite from a lower 12-inch vein of quartz. The vein quartz is very drusy, and small, slender quartz prisms project into the cavities. Much iron oxide is present, and some sulphides. The vein is reported to have given high assays in gold.

ROSENTHAL PROSPECT.

The Rosenthal prospect comprises the Sun, Moon, Morning Star, and Evening Star claims, all located on the high ridge which borders the Fishhook Creek basin on the northeast. The developments consist of two adit tunnels and a fair trail from the valley of Fishhook Creek. The longer tunnel, on the west side of the ridge, is about 95 feet in length and is driven along the vein which cuts the quartz diorite country rock. The vein, which consists of white, somewhat banded quartz, strikes N. 40° W. and dips 10° SW. It ranges from 1 to 3 feet in thickness and carries some visible specks of free gold and finely disseminated pyrite. This flat-lying vein is close to the mountain top, and the amount of ore, even if continuous in all directions, is necessarily small, as the projected plane of the vein comes the surface in all directions within a few hundred feet of the main

tunnel. On the east side of the mountain a 30-foot tunnel, driven on the same vein, is not now accessible. The gold is reported to be irregularly distributed, rich ore being closely succeeded by almost barren quartz. At the entrance of the longer tunnel is a pile of quartz, estimated to contain over 100 tons.

SHOUGH PROSPECT.

The Shough prospect is located on the Oregon group of claims on the west side of the Little Susitna Valley, 2 miles north of Fishhook Creek. The camp and workings are at an elevation of 3,550 feet, 1,800 feet above Little Susitna River. Development work on these claims was begun in the spring of 1913, and the improvements consist of a horse trail built from the main valley trail to the workings, an adit tunnel, which at the time of the writer's visit was 35 feet long, a shallow shaft, and several open cuts.

The shaft was sunk on "vein No. 1," a quartz vein which strikes N. 13° E. and dips 62° W. It is reported that the vein, which cuts a pinkish decayed diorite country rock, reached a maximum thickness of 15 inches. Remarkably rich assays, showing several thousand dollars a ton in gold, are said to have been made on ore from this vein. On the mountain slope below the shaft an adit tunnel was driven for the purpose of intersecting vein No. 1. In this adit another quartz vein with a greatest thickness of 12 inches was encountered and followed. The vein strikes in general about N. 36° W. and dips 45° E., but both strike and dip change greatly within short distances. The country rock near the tunnel breast is a dark blue-gray diorite, and the quartz is considerably shattered, and much stained with copper carbonate.

A third vein, imperfectly exposed in open cuts, is said to reach a width of 3 feet. Its general strike is east and its dip 68° N.

Notwithstanding the high assays reported from these veins, the vein matter shows little or no free gold and yields unsatisfactory returns when mortared and panned. The principal visible metallic minerals present are azurite, what appears to be chalcocite, iron oxide, and some galena. In the shallow depths reached, however, the quartz is more or less oxidized and the iron oxide probably represents original pyrite. Insufficient work had been done at the time the property was visited to determine the permanency of the veins. The presence of tellurides has been suspected but a small sample of ore failed to show tellurium on chemical analyses in the Survey laboratory.

The Shough prospects lie just east of the line of a fault zone cutting the diorite. This fault has been traced for a distance of more than 2 miles in a northeast direction, and several prospects have been located near it. The relation of this fault to the veins near it has

not yet been determined, as little development work has been done along it, and the surface exposures are unsatisfactory. It may be, however, that the fault has offered a passage through which mineralizing solutions have circulated, and that the veins near it have a close genetic relation to the fault.

HATCHER PROSPECT.

The Hatcher prospect comprises three claims known as the Little Gem group, in the upper basin of Archangel Creek, about a mile above the mouth. The claims were staked in August, 1913, and were not visited by the Survey party, as no development work had been done at the time that portion of the area was mapped. It was reported in September that a tunnel 15 feet long had been driven on this property, disclosing a quartz vein from 1 to 10 inches thick, cutting the quartz diorite country rock. This vein is said to be traceable for 1,500 feet along the surface and to carry considerable gold. A large specimen from this vein showed abundant free gold in coarse specks. It is planned to install an aerial tramway and a 3-stamp prospecting mill on this property.

MCCOY PROSPECT.

The McCoy prospect includes a group of 19 claims on the east slope of the mountain which lies west of the lower Reed Creek valley. The claims were located on June 28, 1913, and prospecting during the year was confined to digging open cuts to uncover the vein croppings. At the time the property was visited no one was working on the claims. About 20 open cuts were examined. None of these is large, and only a part of them reached undisturbed bedrock. Several of the cuts had a little quartz on the dumps, and one showed 4 inches of clayey gouge in place, containing a little quartz. The country rock on this mountain is all coarse quartz diorite, with some inclusions or segregations of a gray sugary phase of the diorite. It is reported that the best showing of quartz on the property is north of the cuts visited. There are said to be three veins, the largest reaching a maximum known thickness of 7 feet. The veins are reported to strike northwest and to dip southwest.

BARTHOLF–ISAACS PROSPECT.

The four claims of the Bartholf-Isaacs prospect are located in the upper basin of Archangel Creek, about a quarter of a mile above its mouth. They were staked in June, 1912, and only assessment work has been done on them. No one was working on these claims at the time the area was surveyed, and they were not visited by the writer. It is reported that five open cuts have been made which show the vein at its greatest size to contain 2 feet of quartz and 5 feet of ıd to cut quartz diorite.

GRIMES PROSPECT.

The Grimes prospect comprises a group of eight claims, known as the Dolores group, situated on the north side of the ridge which divides the Fishhook Creek drainage basin from that of Archangel Creek. The ground was staked in 1912. The developments consist of a number of open cuts distributed throughout a vertical range of 300 feet and supposed to be on the same vein. The line of cuts strikes a little east of north, but little could be seen of the vein in place, as the sides of the cuts have caved. The lowest cut, at an elevation of about 3,600 feet, shows on the dump pieces of quartz from a vein at least 10 inches thick. The quartz shows some banding and contains bits of altered country rock but is for the most part rather massive white quartz, somewhat iron-stained. The country rock is quartz diorite, cut by a set of joints striking N. 15° W. and dipping 43° SW., and the vein is probably a filling of a joint of this set. Another cut, at an elevation of about 3,200 feet, has on the dump considerable rusty, banded quartz stained with malachite. The vein is evidently at least 6 inches thick. Another open cut above the two already described is said to expose 14 inches of quartz which carries sulphides and free gold.

RAE PROSPECT.

The Rae prospect consists of four claims called the Jennings group, situated on the divide between Fishhook Creek and Little Susitna River, 1 mile north of the east-west portion of Fishhook Creek. The claims lie in an area of more or less gneissic quartz diorite, which is cut by a considerable fault or shear zone. Two open cuts on the Fishhook Creek side of this property were examined. The larger of these cuts was dug from the bottom of a steep gulch, at an elevation of about 4,000 feet, or 1,100 feet above the valley floor, and extended 15 feet into the mountain side. The country rock is deeply oxidized and decayed gneissic diorite, and the cut was driven on a layer of sticky yellowish clay or gouge from 8 to 18 inches in thickness, striking in a general northeast direction and dipping 43° N. Some quartz occurs in the clayey material and contains free gold, chalcopyrite, pyrite, galena, and copper carbonates.

A second open cut, 20 feet above the first, shows the same altered country rock, with thin rusty seams. The little work done on these claims is insufficient to either prove or disprove the presence there of valuable ore bodies.

SAN JUAN PROSPECT.

The San Juan group of two claims is on the crest of the high mountain ridge which forms the west valley wall of Little Susitna River just north of Fishhook Creek. The open cuts on these claims were

not seen by the writer, but it is reported that a ledge 9 feet wide has yielded encouraging assays. Pieces of ore said to have been taken from the property appear to be pegmatitic in character, with large quartz and feldspar crystals. If this rock proves to be workable ore, it is of different character from the other proved ore bodies of the district.

MISCELLANEOUS PROSPECTS.

A number of gold lode prospects have been staked in the district, about which little could be learned and which were not visited. Some large quartz veins of low gold content are reported in the upper part of Little Susitna Valley. A prospect on a high ridge at the head of Purches Creek, a northern tributary of Willow Creek, is said to contain quartz showing considerable free gold. Several hundred pounds of this ore was back packed by the owners to the head of the road on Fishhook Creek, in order to send it to a smelter. A vein on Shorty Creek about 2 miles above its mouth is said to have been stripped for 300 feet, and to show 3 feet of ore. Many other claims have been staked on which insufficient work has been done to demonstrate whether or not they will ultimately develop into mines.

SUMMARY.

PRODUCTION OF DISTRICT.

Of the three producing mines in this district one has been operated for six years, one for five years, and one for two years (in 1913). Two are equipped with stamp mills and one with a Chilean mill. All these mills can be operated only during the short summer season, and the total milling done is the approximate equivalent of 1 stamp of 1,000 pounds dropping for 150 months running time. From this small amount of ore treated, a total of nearly $600,000 worth of gold has been recovered, and nearly one-third of this amount came from ore mined in 1914. The total tonnage milled to the end of 1914 is about 17,200 tons, and the average recovery from the ore is approximately $34 a ton in gold, with some silver. This does not include most of the gold and silver contained in the concentrates or in several thousand tons of tailings which have been stored for future treatment. It is probable that the actual gold content of the ore crushed averaged at least $40 a ton. The production of the district by years is given in the following table:

Production of lode mines in Willow Creek district.

Year.	Gold.		Silver.[a]	
	Ounces.	Value.	Ounces.	Commercial value.
1908	87.08	$1,800	6.88	$3.64
1909	1,015.87	21,000	80.25	41.73
1910	1,320.15	27,290	104.29	56.31
1911	2,505.82	51,800	197.95	109.91
1912	4,673.02	96,600	369.07	226.97
1913	4,883.94	100,960	385.83	233.42
1914	14,376.28	297,184	1,330.00	735.00
	28,862.16	596,634	2,474.27	1,406.98

[a] The silver content recovered from the gold bullion is estimated.

In addition to the gold taken from the gold lodes, placer gold valued at about $30,000 was recovered in this district between 1897 and 1914.

FUTURE OF LODE MINING.

In both the number of tons of ore crushed and the value of gold recovered the year 1914 showed an increase over any preceding year, although the largest mill was not put in operation until the season was half over, a shortage of water throughout portions of the summer seriously curtailed mill operations in two plants, and the third was running only a part of the time on account of breakdowns. On two of the larger properties considerable reserves of ore have been opened up, and the prospects are bright for a prosperous season in 1915. Plans are underway for the installment of new machinery at one of the mines, and small mills will likely be installed on two or three properties not previously productive. It is therefore believed that the output from gold lode mines will tend to show a steady increase.

EXTENT OF MINERALIZED AREA.

As has already been stated, the area in which gold-bearing lodes have so far been found is so small that a circle 6 miles in diameter includes all the important mines and prospects. The location of the places where gold lodes have been found is shown on figure 5 (p. 61). It is by no means certain, however, that the lodes are confined to the small area indicated by the present discoveries. Prospecting has naturally been most vigorous near the producing mines, and later discoveries have each year extended the known limits of the mineralized area. Since all the proved lodes occur within the area of the quartz diorite intrusive mass, it is to be expected that the future discoveries will also be made in rocks of this type. Most of the lodes that have been discovered occur within a few miles of the southern border of the quartz diorite mass, but a reported find of rich gold

quartz on the head of Purches Creek, a northern branch of Willow Creek outside of the area here mapped (Pl. II), tends to show that the gold-bearing veins are not confined to the borders of the intrusive mass but may occur well within it. Any extension of the limits of the district which contains quartz veins that cut quartz diorite will necessarily be in the directions in which the intrusive rocks occur, namely, to the north and east. In most of this region but little prospecting has been done. The unmapped area north and northeast of the Willow Creek district, including the headward basins of Purches and Peters creeks, Kashwitna River, and Montana and Sheep creeks, is thought to contain large masses of granitic intrusive rocks similar to those in which gold-bearing veins have been found and is believed to offer a promising area for prospecting. It is difficult of access, however, much of it lies far from timber, and even sufficient brush for camping purposes may in places be difficult to obtain. No trails lead to this area, but it may be approached in winter from the Susitna Valley by sled and horses may be taken into the region by following the mountain slopes on the east side of Susitna Valley north from Willow Creek. The upper basins of Moose, Granite, Kings, and Boulder creeks and Chickaloon River, all tributary to Matanuska River, lie in the area of granitic intrusives. Some of these valleys are known to contain placer gold, and they deserve careful prospecting for gold lodes.

DEPTH OF MINERALIZATION.

Only general information is available as to the depth below the surface to which the mineralized veins extend. Most of the prospects are high on the mountains, and mining has been conducted almost entirely by means of tunnels and stopes rather than by sinking. So far as is known to the writer, no single vein has been opened over a vertical distance of more than 200 or 300 feet below the outcrop. The veins all cut quartz diorites which so far as known have an indefinite downward extension. In these rocks the walls of the veins are everywhere of much the same chemical and physical composition, and no reason is known why the walls of the veins should exert a controlling influence on ore deposition at one level rather than at another. The character of the veins and the association of their metallic minerals is characteristic of veins deposited at considerable depth. The ores mined are composed of the original vein material and are practically free from alteration and from either enrichment or leaching. The mineralization in such primary veins has generally a considerable vertical range, and there is no reason to fear that in a country rock of uniform character, and with primary veins of deep-seated origin, mining operations will penetrate below

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which fails to show considerable free gold on panning is not deemed worthy of further attention. Until 1912 there was no assayer in the district, and it was often several months before the returns from samples sent either to Seward or Seattle for assay were available. Naturally therefore the prospector relied on the immediate information obtained from his mortar and pan. The presence of tellurides in a sample said to have come from this district indicates that assays may be desirable for certain of the ores.

FUTURE OF PLACER MINING.

Since 1905 the placer gold production of this district has been small. Although considerable prospecting was done, the only ground discovered that has proved rich enough to justify mining under present conditions was that first staked on Grubstake Gulch and below its mouth on Willow Creek. Nevertheless there are many claims on lower Willow Creek that yield encouraging prospects, and it is reported that areas there are suitable for dredging. When the railroad is completed to this district it will probably reduce mining costs so much that ground not now available can be worked at a profit, and the district may become the scene of a vigorous placer mining industry.

The railroad to be built from the Matanuska coal field to tidewater on Knik Arm will furnish coal for the Willow Creek district at less than the present cost. It may also be possible to obtain power at a considerably lower cost by building a tram road or an electric transmission line from the Moose Creek coal outcrops.

An increase of power from the present plants could be obtained by bringing the same volume of water to the mills under greater head. Most of the streams in the upper portions of their basins have steep gradients, and additional head could in most places be obtained at a rather small expense.

What appears to be the most feasible suggestion for power for the mines is the installation of a single plant on Little Susitna River near the canyon to supply hydroelectric power to all the mines of the district. The maximum power consumption for the whole district in 1913 was probably less than 75 horsepower during the running season, and the regular fall diminution of run-off caused the closing down of all the mills in September, yet a measurement of the flow of Little Susitna River at the canyon, on September 13, by R. W. Davenport, of the United States Geological Survey, showed sufficient run-off at that late date to develop 12 horsepower for each foot of fall.[1] The stream gradient is there quite steep, and even with a much smaller run-off than that measured it would be easily possible to develop several hundred horsepower, which would be available for a considerably longer period than can be obtained with the present installations. Although nothing is known of the winter discharge of the Little Susitna, it seems likely that the operating season could be almost doubled in length and enough power developed to provide for expansion for some time to come. If it seemed desirable, an auxiliary steam plant to furnish power in the winter could be provided, the coal to be brought from Moose Creek.

Timber for use in mines must be brought several miles, but fortunately not much is needed. Nearly all the tunnels need timbering near the surface, especially those driven through talus or loose surface material, but in the solid quartz diorite, beyond the area of surface disintegration, the rock holds excellently and very little timber is used.

Prospecting is carried on in this district by rather primitive methods. The gangue of the gold-bearing veins is predominantly quartz, and the prospector confines his attention to the search for quartz as float, or in place. The determination of gold in the quartz discovered is almost altogether made by means of mortar and gold pan. If the quartz does not contain visible particles of free gold a small piece is crushed in a mortar, and the pulp is panned. Quartz

[1] Ellsworth, C. E., and Davenport, R. W., A water-power reconnaissance in south-central Alaska: U. S. Geol. Survey Water-Supply Paper, in preparation.

the mineralized portions of the veins for some time to come, if the veins themselves are continuous downward, or that the character of the ore will change greatly within a rather wide vertical range.

MINING COSTS.[1]

The development of mining in the Willow Creek district is hampered by much the same adverse conditions as those which affect most inland mining districts in Alaska. The most far reaching of these conditions is the shortness of the summer season, which directly affects the cost of transportation, of labor, and of power. (See p. 18.) Freight can be placed at the mines more cheaply by sled in winter than by any means in summer, so that six months or more often elapse between the dates of shipment of freight from Seattle and its arrival at the mines. The total transportation cost of freight from Seattle delivered at the mines naturally differs according to the location of the delivery point and the bulk moved, but when taken in by the most economical methods ranges from $50 to $85 or more a ton. Surface mining and prospecting are limited by the weather to a period of 150 days or less, and wages for a short season are consequently greater than they would be if steady employment were offered. The ruling wages in the district for miners and laborers range from $100 a month to $5 a day. The present situation, both in regard to transportation costs and labor, will, however, be greatly improved when a railroad is constructed to pass near this district.

For those mines which obtain their ore by underground mining the length of the productive season is determined only by the duration of the time in which the stream flow is sufficient to furnish power for milling. The three mills now installed are all situated near the heads of the stream basins, where the discharge is small, and an adequate supply of water for even their slight power requirements can be obtained for a season of only about 100 days. This places the burden of carrying all the capital expenditures for the year on a very short productive season, necessitates higher wages during the period of operation, and greatly increases the cost of mining. One of the most serious problems which confronts the operators of the district, therefore, is the securing of cheap power which would be available all the year round. Coal occurs on Moose Creek, about 12 miles from the mines on Fishhook Creek, but transportation charges on coal brought from even this near-by locality would, under present conditions, be about $30 a ton, and the cost of this coal delivered at the mine on Craigie Creek would be even higher. Cordwood, delivered at the mines, is said to cost $40 a cord, and gasoline 70 cents a gallon.

[1] The conditions here described will change when railroad communication with Seward is established.

DEPARTMENT OF THE INTERIOR
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BULLETIN 608

THE ROAD PASS REGION, ALASKA

BY

FRED H. MOFFIT

WITH SECTIONS ON

QUATERNARY DEPOSITS, IGNEOUS ROCKS AND GLACIATION

BY

JOSEPH E. POGUE

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PREFACE.

By Alfred H. Brooks.

Broad Pass was discovered in 1898 by George H. Eldridge and Robert Muldrow, of the United States Geological Survey, in the course of their exploratory survey of the Susitna Valley.[1] The Indians had, of course, long known the Broad Pass region as a hunting ground, and some white prospectors had reached the upper Susitna basin before 1898, but so far as known the Eldridge party was the first to reach Tanana waters by this route. Worthy of record is the journey into this region of a party of prospectors, among whom W. G. Jack was the leading spirit. This party sledded up Susitna River in the spring of 1897 to the vicinity of Broad Pass and searched the neighboring district for placer gold.

The salient geologic and topographic features of the Broad Pass region were determined by the Eldridge party, as was also the feasibility of a railway route into the interior by this wide gap. As a result, a railway was planned through this pass and surveys for it were made in 1902.

The increased interest in railway routes from the Pacific seaboard created a demand for further information about this region, and plans for a supplementary survey were formulated in 1912 but had to be abandoned after supplies had been sledded into the interior because of delay in the appropriation. This plan was successfully carried out in 1913 by a geologic party under the leadership of F. H. Moffit and a topographic party under leadership of J. W. Bagley. The fact that a region so large and so remote as that described should have been mapped in one season reflects great credit on Mr. Moffit and Mr. Bagley and their assistants.

The results set forth in this report bring much additional evidence of the availability of Broad Pass as a railway route into the interior. They also show that, though no commercial mineral deposits have been found in the region, yet what is known of the geology gives hope that such deposits may be found. Since these

[1] Eldridge, G. H., A reconnaissance in the Sushitna Basin and adjacent territory, Alaska, in 1898: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, pp. 1–29, 1900.

surveys were made prospectors report the discovery of ore bodies in the Broad Pass region, and, as has been pointed out, this was to be expected from the geologic survey.

The official announcement of the choice of Broad Pass as the route of the proposed Government railroad is made about the time this report is sent to press. This railroad is to run from Seward to Fairbanks. Broad Pass is about 310 miles from Seward and about 150 miles from Fairbanks by the proposed route. It is therefore to be expected that the Broad Pass region will now be the scene of much prospecting, and there is good hope that it may afford profitable mining development.

THE BROAD PASS REGION, ALASKA.

By Fred H. Moffit.

INTRODUCTION.

Broad Pass is a wide glaciated valley (Pl. III, *A*) between the head of Chulitna River and a tributary of the Nenana named Jack River. It is commonly regarded as one of the passes through the Alaska Range, but in reality is part of an east-west valley connecting the heads of the Chulitna and Susitna rivers. The headwaters of Nenana River once flowed westward through it to the Chulitna. The Broad Pass region, as the term is here used, includes the headwater tributaries of Chulitna and Nenana rivers and the heads of some streams flowing into Susitna River.

Previous exploration.—The vicinity of Broad Pass was first visited by Government exploring parties in 1898. In that year G. H. Eldridge and Robert Muldrow, of the United States Geological Survey, accompanied by five others, ascended Susitna River to the mouth of Indian Creek, whence packing their equipment on their backs, they made their way up Indian Creek and through an unnamed valley paralleling the main Chulitna Valley to a pass which they called Caribou Pass and which led them to the upper Jack River Valley. Descending Jack River and the Nenana they reached the mouth of Yanert Fork, where lack of provisions and the lateness of the season compelled them to abandon their hope of reaching Tanana River and to retrace their steps to the Susitna.[1]

The same year (1898) Sergt. William Yanert, Eighth United States Cavalry, with one white companion and an Indian guide, crossed the mountains between Indian Creek and Chulitna River and ascended the Chulitna Valley to Broad Pass and Jack River where, probably through fear of the Tanana natives, the guide refused to accompany him farther. In his report[2] to Capt. Glenn, Yanert states that he was directed by the Indian to cross the "tributary of the Tanana," Jack River, which he then thought to be the Cantwell

[1] Eldridge, G. H., A reconnaissance in the Sushitna Basin and adjacent territory, Alaska, in 1898: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, pp. 1–29, 1900.

[2] Compilation of narratives of explorations in Alaska, Washington, pp. 677–679, 1900.

(Nenana) and was told that a trail would be found on the other side. He soon discovered the trail and after following it a short distance came upon tracks of white men that he rightly conjectured to be those of the Eldridge party, for they had passed that point only a few days before. The lack of all food except game, the loss of his shoes, and the knowledge that the Eldridge party was ahead of him, led Yanert to give up any further attempt to reach the Tanana and to return to the Susitna.

In 1902 an exploring party under Brooks crossed the Alaska Range from Cook Inlet by way of Rainy Pass, at the head of Skwentna River, and made its way northeastward along the flanks of the range to Nenana River and thence to the Tanana and the Yukon. The party crossed Nenana River above the mouth of Yanert Fork, but was obliged to ascend the fork for more than 20 miles before they could find a ford. Although the members of this expedition visited only the border of the Broad Pass region, they added something to the geographic and geologic knowledge of it.[1]

In 1902 and 1903 a reconnaissance survey for a railroad from Seward to Tanana River was made by private persons, who followed the Susitna and Chulitna river valleys up to Broad Pass and thence went down Nenana River to its mouth. As is common in such work, the information collected by the engineers during this survey did not become generally known.

Most of the information concerning the Broad Pass region obtained prior to 1913 was collected by members of the four expeditions already mentioned. Yet many white men—prospectors and hunters—have visited the region, coming into it for short periods and going away without leaving permanent record of their presence.

Topographic and geologic reconnaissance surveys were made by the United States Geological Survey in the adjacent Bonnifield[2] and Valdez Creek[3] districts in 1910. That work carried earlier surveys in the Copper River basin westward to Susitna River and like surveys in the Tanana Valley southward into the Alaska Range, so that with the completion of surveys in the Broad Pass region, a wide section of the range, extending westward from Delta to Nenana River, has been mapped.

Surveys in 1913.—Two parties were sent into the Broad Pass region in 1913; one, a topographic party of six men, was in charge of J. W. Bagley; the other, a geologic party of five men, was in charge of the writer.

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[1] Brooks, A. H., The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, 1911.

[2] Capps, S. R., The Bonnifield region, Alaska: U. S. Geol. Survey Bull. 501, 1912.

[3] Moffit, F. H., Headwater regions of Gulkana and Susitna rivers, Alaska: U. S. Geol. Survey Bull. 498, 1912.

Provisions for both parties were sent to Valdez Creek in March, 1912, but could not be used during the following summer because the appropriation for work in Alaska was made too late to be available that year in a region so remote. The work that had been planned for 1912, therefore, could not be carried out and was postponed to the next season. In the early months of 1913 more provisions were sent to Valdez Creek to replace such of the old supplies as were believed to be unfit for use. The two parties started for Valdez Creek June 8, after spending several days at Chitina in repairing the pack and camp outfits. The parties first followed the military road to Meiers Roadhouse, 124 miles from Chitina. At this place it was thought best, on account of the lateness of the spring and the consequent scarcity of grass, to leave the road and go westward to Maclaren River through a country lower than that of the trails leading westward from Paxson or from Yost's road house. Crossing Gulkana River at the foot of Gulkana Lake, the parties ascended the Middle Fork of the Gulkana and Lake Creek to the Tangle Lakes, and then followed the usual route across the two branches of Maclaren River, down Coal Creek and past the Roosevelt Lakes to the placer camps on Valdez Creek, where they arrived June 28. A number of days were employed at Valdez Creek in preparing for the work ahead. Provisions were separated out and sacked for use during the summer and on the return trip to the coast; a boat was built after the necessary lumber had been whipsawed; and finally the provisions, camp equipment, and horses were taken across Susitna River July 8, just one month after the parties started from Chitina.

The two parties worked near each other for a few days, then separated and did not meet again until the season's work was completed. The course followed by both was first to the southwest, then to the west, the north, and back to Valdez Creek. About 55 days were devoted to topographic and geologic mapping, but the work was interrupted by frequent rains during the summer and was ended finally by a heavy fall of snow from August 26 to 28. Both surveys were of a reconnaissance nature. The photographic method was employed in topographic mapping, Mr. Bagley being assisted in the photographic work by L. G. Steck. By using this method the topographers were able to survey a much larger area than they could have otherwise covered. The area mapped topographically is about 2,500 square miles.

About 1,700 square miles was mapped geologically. The writer was assisted in the field by Joseph E. Pogue, who also prepared the geologic map in the office and, in addition to writing the sections on the Quaternary deposits, igneous rocks, and glaciation, has done much other work connected with this report.

GEOGRAPHY.

Location and area.—The topographic map (Pl. I, in pocket) accompanying this report represents a mountainous area whose limits are defined by parallels 62° 57′ and 63° 51′ north latitude and by meridians 147° 25′ and 149° 15′ west longitude, and which comprises about 3,700 square miles. This area lies at the northernmost bend of the great arc formed by the Alaska Range. It includes the axis of the range, but in the main it lies south of that axis, embracing

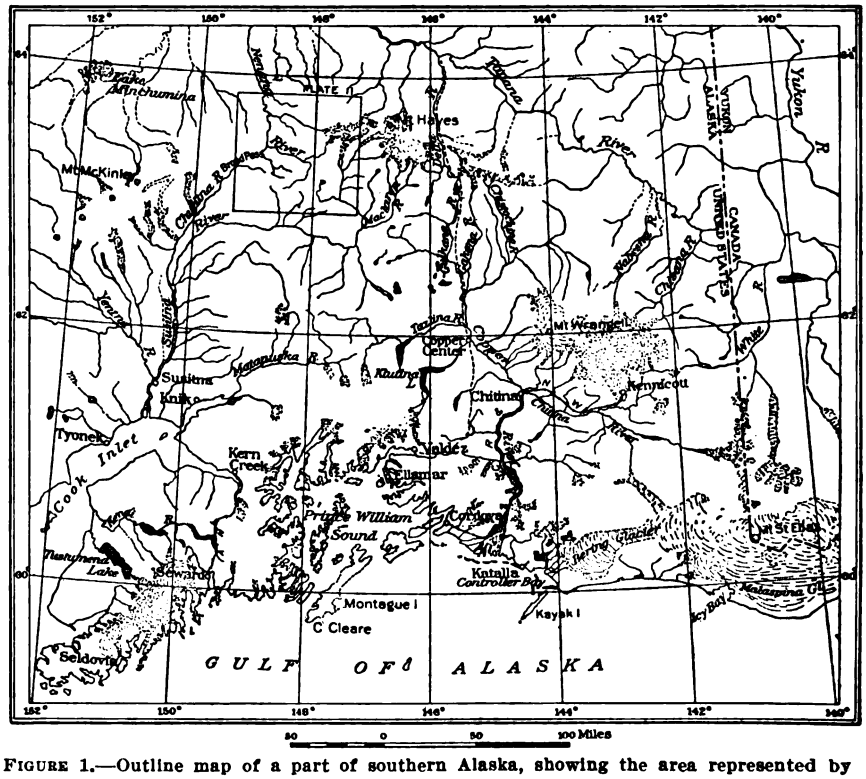
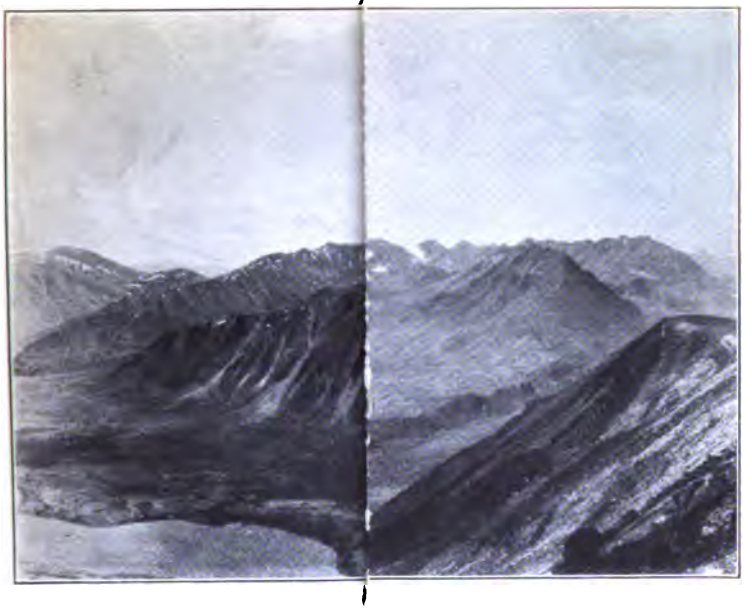


FIGURE 1.—Outline map of a part of southern Alaska, showing the area represented by Plates I and II (in pocket).

part of the mountainous country between the Alaska Range proper and Susitna River. The location of this area is shown on figure 1.

Topography.—Most of the area considered is rugged and of high relief. It lies near the highest part of the Alaska Range east of Mount McKinley and includes many high peaks. On the other hand, it embraces also the lowest pass through the range. Cathedral Mountain, 13 miles east of the boundary of the area, stands 12,340 feet above the sea; Mount Hayes, 16 miles farther east, is 13,740 feet high; the highest mountain within the mapped area reaches an elevation of 9,000 feet. The highest mountain south of Broad Pass within



the area mapped stands about 6,700 feet above the sea, but in general the mountains between Broad Pass and Susitna River do not exceed 6,000 feet and are therefore at least 1,000 feet lower than those of average height in the main range to the north. The mountains about Butte Creek, in the southeastern part of the area, reach elevations over 6,000 feet. Broad Pass itself is about 2,500 feet above the sea, or practically the same elevation as Susitna River at the mouth of Valdez Creek. Yanert Fork at its mouth is 2,000 feet above the sea. Therefore the maximum relief of the areas, as is shown more clearly on the topographic map, is nearly 7,000 feet.

The mountains of the northern, western, and southern parts of the area have the rugged outlines of a recently glaciated mountain region. High-walled cirques (Pl. IV, *B*), truncated spurs (Pl. VII, *A*, p. 18), straightened valleys, and oversteepened valley slopes are characteristic features of the topography. On the other hand, the mountains of the eastern and central parts show smoother contours and are separated by lowland areas dotted with glacial lakes and strewn with morainic débris (Pl. V, *A*).

Drainage.—The Broad Pass region is drained primarily by Nenana and Chulitna rivers. A part of the drainage, however, passes to the east and south into Susitna River.

Nenana River and its principal tributary, Yanert Fork, originate in glaciers descending from the west slopes of Cathedral Mountain. The upper Nenana may be regarded as belonging properly to a drainage basin south of the Alaska Range, either the Chulitna or the Susitna, and Yanert Fork as belonging to the drainage north of the range. Yanert Fork is fed by a great glacier (Pls. V, *B*; VI, *A* and *B*, p. 16) flowing directly west from Cathedral Mountain, but the Nenana receives its headwaters from a small glacier on the ridge running southwest from the main peak and forming the divide between the two streams. Most of the ice streams on the south slopes of Cathedral Mountain unite to form the great West Fork Glacier of Susitna River. At its beginning Nenana River takes a southerly course, but it soon turns to the west and flows for 25 miles in a wide valley connecting the heads of Chulitna and Susitna rivers; then, instead of holding its westerly course and joining Chulitna River, it turns abruptly north through a minor ridge of the range, resumes its westerly course for a few miles, and finally flows northward in a deep narrow valley (Pl. VII, *B*, p. 18) through the Alaska Range.

Nenana River in its upper course, below the place where it first turns westward, flows sluggishly and meanders widely through open country. On the other hand, in its course from the place where it first turns northward into the mountains to the place where it crosses the axis of the range it runs in deep canyons or in narrow valleys.

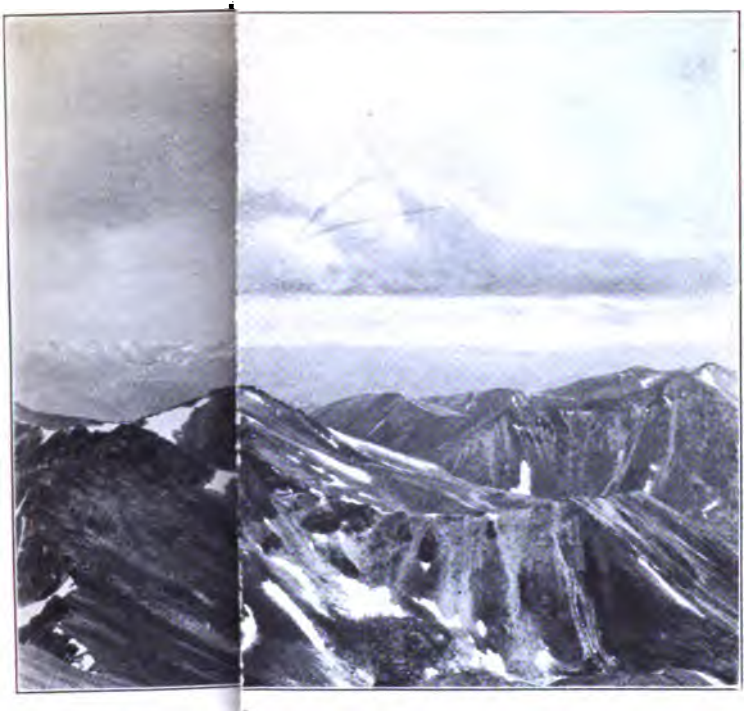
Its current, although swifter in this lower course than above, is not so rapid as that of Yanert Fork or of Delta River, which cuts through the range in a similar way farther east.

The principal tributaries of Nenana River, aside from the Yanert Fork, are Wells Creek on the north and Jack River and Brushkana Creek on the south. The eastern branch of Wells Creek, which joins Nenana River about 15 miles above the mouth of Jack River, and the Nenana itself for 5 or 6 miles above Jack River, lie in a minor intermontane valley that extends westward from the Nenana Glacier. Brushkana Creek, which is as large as the Nenana at the junction of the two streams, drains the central part of the area mapped and flows for the most part in a lowland country covered with marshes and small lakes. Jack River, on the contrary, is surrounded by high mountains (Pls. IV, *A* and *B*, p. 12). Its principal branches flow in deep, rocky canyons and its current is swift. The waters of Jack River, like those of the Brushkana, are clear.

Chulitna River drains the western side of the area. It is a large stream, but only the upper part of two of its branches lie within the area here mapped. It receives the water from many large glaciers in the vicinity of Mount McKinley, as well as from several eastern tributaries, and unites with Susitna River about 75 miles from the coast.

Butte, Watana, and Deadman creeks are the largest tributaries of Susitna River that rise within the area mapped. They can hardly be considered as belonging properly to the Broad Pass region, but they lie within the area of the summer's work. Butte Creek flows from Butte Lake, the largest lake shown on the map.

Routes and trails.—The Broad Pass region has been reached by three routes. The earliest explorers and prospectors approached it from the south through the Susitna and Chulitna valleys. Later hunters and prospectors came into it from the Tanana Valley through either the Nenana River or the Wood River valley. Others approached it by way of Valdez Creek and over the trails leading westward from the Military Road. All three routes have certain advantages and all offer difficulties. For summer use the route from the east is probably the best. At the outset it offers the advantage of a good wagon road from Valdez or Chitina, and farther on, between the road and Valdez Creek, of trails that are being traveled more and more each year. In contrast to this, the route from Cook Inlet is little used. No trails have been marked out in the valleys of Indian Creek or the Chulitna and no means of transportation have been established on Susitna River. The route from the Tanana Valley is traveled occasionally by hunters and less often by prospectors, but no trails have been made.



In winter the Susitna and Chulitna rivers, Nenana River, and the upper Susitna River afford practicable routes for freighting such supplies as would be required by prospectors in the Broad Pass region. Most of the supplies and mining equipment taken to Valdez Creek since 1907 have been sledded over the ice of Gulkana and Susitna rivers, yet in some of these years a part of the supplies has been brought from Fairbanks on the Nenana and Susitna rivers.

In the Broad Pass region travel has been so slight, and the visits of white men have been so infrequent and their wanderings so variable, that no usable trails have been established. In places the Indians, passing from one hunting ground to another, have followed trails that can be traced readily for short distances. In places also wandering caribou and moose have left trails that are still more conspicuous but that for the most part are of little benefit to travelers. It is evident, then, that all who now go into the region must choose their own ways. Travel, however, is not difficult for either horses or men where courses in the higher ground can be used. The best going is generally above timber line, at elevations between 2,800 and 3,500 feet above the sea. At such elevations trees and brush are absent, soft ground is less common, for the steeper slopes give better drainage, and grass for horses is most plentiful and of the best quality. The supply of firewood is less abundant than in the lower valleys, but willows for cooking and for tent poles can usually be found at elevations below 3,200 feet. In the lowlands the swamps and lakes make travel slow and tiresome.

Some of the larger streams offer difficulties to travel both because of their depth and swift currents and because of quicksand. Nenana River and Yanert Fork may be difficult or even impossible to ford at times of high water, but on cool days later in the summer may be forded safely if care is used in choosing the place. A few of the small streams are so full of granite bowlders that horses are likely to have trouble in fording them.

Railway routes.—Broad Pass offers one of the most favorable railway routes from the Pacific seaboard to the Tanana and Yukon basins and has been chosen for the route of the Government railroad from Seward to Fairbanks. The Chulitna, flowing into the Susitna on the south, and Jack River, flowing into the Nenana, a tributary of the Tanana, on the north, both head in Broad Pass. It therefore marks the watershed between Cook Inlet and Yukon drainage. The waters of the Nenana in the past ran through Broad Pass into the Chulitna, but were diverted by the glacier that formerly occupied the region. Since the disappearance of the ice the drainage has not reverted to its preglacial course.

The approach[1] to Broad Pass from the south, along the headwaters of the Chulitna, is, so far as known, a gradual ascent, and a railway route of comparatively low grade could probably be found. The pass itself is a flat about 4 miles wide, presenting no engineering difficulties. It stands about 2,500 feet above sea level, which is about 700 feet lower than Isabelle Pass, on the route from Valdez and Chitina to Fairbanks. North of Broad Pass the railway route would be down the valley of Jack River to the Nenana, and here, too, a good grade could probably be found. The main Alaska Range would be traversed by the valley of Nenana River, which for about 10 miles flows through a steep-walled canyon.

Though Broad Pass probably affords the most feasible railway route, because it is most direct, there are other low divides leading from the Susitna into the Nenana basin. Thus a gravel-floored flat connects the upper Susitna Valley near Valdez Creek with Nenana River. Another low pass lies between the headwaters of Deadman Creek, flowing into the Susitna on the south, and Brushkana Creek, flowing into the Nenana on the north.

Climate.—A lack of records of rainfall, temperature, or other meteorologic data makes it impossible to discuss the climate of the Broad Pass region in other than general terms. The climate is that of a high mountainous country of abundant rainfall, with moderate summer heat and with winter temperatures that occasionally go lower than 40° below zero. The precipitation is much less than that of the southern coast of Alaska, but probably more than that of the Copper River basin and the Nenana Valley. Old choppings in several places along the Tanana River show that the snow was 2 or 3 feet deep when they were made. This does not indicate the total winter snowfall, but it probably gives a fairly correct idea of the average depth of snow in the main valleys in middle or late winter. Snow persists in deep gulches on the high mountains during most of the summer—occasionally throughout the year—but it probably is not correct to say that any of the peaks within the area mapped rise above the summer snow line. New snow is seen on the high mountain tops after almost every summer rain and sometimes comes well down on the mountain sides.

The length of the placer-mining season in the Valdez Creek district, except for underground work, has been regarded as 90 to 100 days. The season's length is governed in some measure by the necessity of leaving Valdez Creek while there still is grass for horses on the trail to the coast, and is therefore shorter than it would be if transportation facilities were more favorable. In 1913, by placing

[1] Railway routes in Alaska: Alaska Railroad Comm. Rept., H. Doc. No. 1346, 62d Cong., 3d sess., 1913.

feed at different points along the trail between Valdez Creek and Paxson, the miners were enabled to continue work almost until the 1st of October.

Climatic conditions in 1913 were somewhat different from those of most years since mining began in this district, for the early part of the season was unusually dry and a deep snow came very early in the fall. Little rain fell from the time when the snow began to melt in the spring until after the 1st of July, as a result of which fires were numerous and interfered much with the topographic work. The rainfall was considerable during the rest of the season and the rainy days were cold and disagreeable. A severe storm extending over much of Alaska began in the last week of August and continued for several days. Between the 26th and 28th of August from 18 to 24 inches of snow fell in the Broad Pass and Valdez Creek regions. The survey parties left Valdez Creek early in September, but it was learned that most of this snow had disappeared from the lower valleys by the beginning of October.

Vegetation.—In a discussion of vegetation of this region the distribution of timber and the supply of grass for horses are the particulars most likely to be of interest to travelers. A sketch map (fig. 2) is presented to indicate where spruce timber is found. It shows, further, that most of the region is above timber line, for all the area not covered with timber is above the elevation for that locality at which spruce grows. The elevation of timber line is not constant; it varies in different localities and ranges from 2,500 to 3,000 feet above the sea.

Spruce is the only valuable timber in the region, although cottonwood grows on many of the river bars, especially those of Jack and Nenana rivers, and might be used for some purposes if spruce could not be obtained. The best spruce timber seen in the region is on Butte Creek and is the source of supply for the miners of Valdez Creek. The largest trees cut there would furnish timbers a foot square and 16 feet long. Spruce of fair quality and size grows in places on Susitna River and on the lower part of Jack River, but in the rest of the timbered area the trees are scattered and scrubby, and although excellent for fuel would either make a poor quality of lumber or be altogether unsuited for that purpose.

Willows large enough for tent poles and firewood grow on nearly all the smaller streams up to an elevation of about 3,200 feet above the sea. As a rule they do not thrive on the bars of the larger creeks where unprotected from exposure, but seek the small tributary streams that have incised their channels deep into the gravel deposits or bedrock or that flow in narrow valleys between the mountains.

It thus happens that many good camp sites are hidden away in places where at first it seems as if none could be found.

Alders are not common on the upper Susitna, but are fairly plentiful along stretches of Nenana River, although very much less so than on the lower Copper and Susitna rivers and on the southern coast of Alaska.

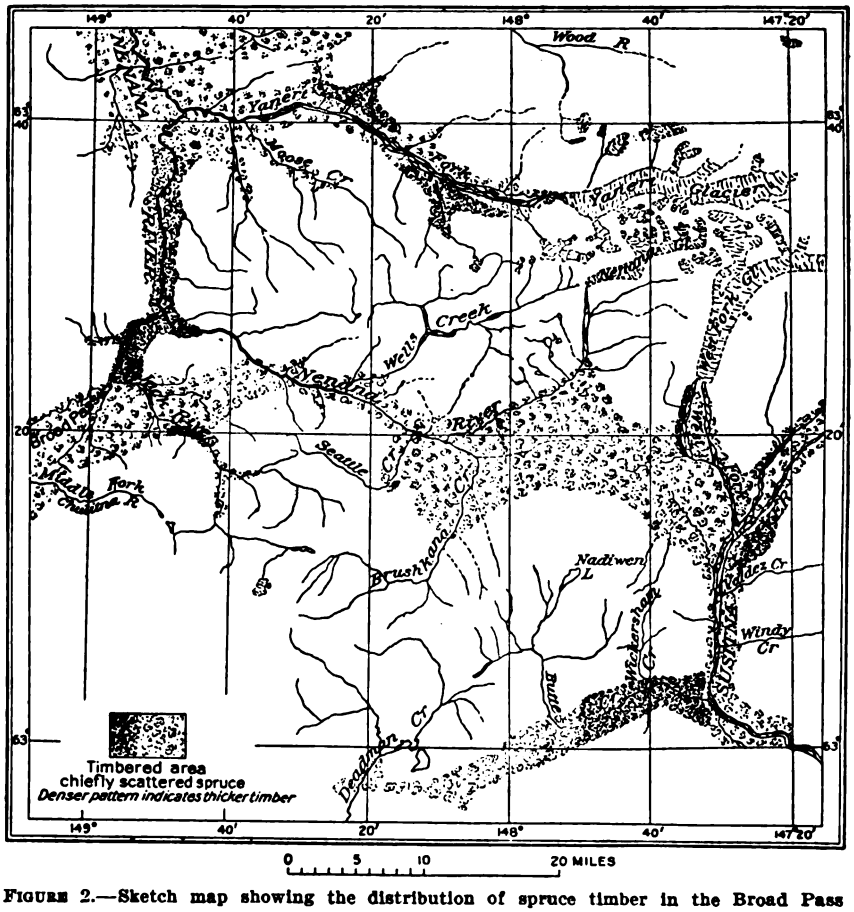


FIGURE 2.—Sketch map showing the distribution of spruce timber in the Broad Pass region.

Grass is abundant in the Broad Pass region in the places best suited to its growth. The lower parts of wide valleys and the gravelly flats of the larger streams are not such places, and grass is rarely found there in large amount. It grows luxuriantly, however, in many small valleys near timber line or at about the elevation where willows and alders thrive best. Steep banks along streams, the faces of benches on hill slopes, and the protected angles at their bases are commonly covered with a fine carpet of grass. On the western or

Chulitna side of the area under discussion the tall grass called red top grows and forms the matted tangle of stems so commonly encountered in the Cook Inlet and lower Susitna region. It does not grow so luxuriantly, however, as in that region and is not so widely distributed on the eastern or upper Susitna side of the area.

Bunch grass, as it is commonly called, grows on many dry, gravelly flats. It cures on the stalk and is valuable as horse feed long after frost has killed the more luscious, ranker red top. The individual plants have the habit of growing somewhat apart from one another with bare spaces between, and in the spring the young blades come up through a base of old, dry, matted stems, building up a little clump of grass, which is raised above the surrounding ground level. This takes place year after year, and thus are formed the characteristic bunches from which the grass gets its name.

The date of the first appearance of grass in the spring depends on the locality and on the melting of the snow. It is a custom of the miners on Valdez Creek to turn their horses loose when the freighting is finished and the summer's wood supply is gathered, and to provide them with forage as long as they will return to the camps for it. The horses prefer the young, tender grass and rushes that they find on the bars of Susitna River to dry feed, and in most years will not return for hay and oats after the 10th of May or thereabout. The spring of 1913 was an exception to this rule, for the horses had to be fed for 10 days or 2 weeks longer than usual.

Grass grows rapidly in this region when it has once started, and by the 1st of July it is large enough to make good forage. It is killed quickly by the early fall frosts, so that by the 10th of September it is necessary to provide stock with feed other than that furnished by the country itself.

Several species of leguminous plants that are known by the general name "pea vine" grow on gravel bars of the larger streams and in a few places on the hill slopes. They furnish a most nourishing food for stock in the late summer and fall. Horses are exceedingly fond of pea vines and will leave any other forage for them, yet they will scarcely touch the plants early in the summer, before the seeds have ripened. Pea vines grow luxuriantly on the lower part of Jack River and are more abundant there than in any other place known to the writer.

Several kinds of berries are native to this region. Of these the blueberry is the most widespread and abundant. It thrives best near timber line and furnishes a welcome addition to the diet in August. A few currants and "low-bush cranberries" were found, but hardly in sufficient quantity to satisfy the appetites of the party at one meal. The scarcity of these two kinds of fruit was unex-

pected, for both are locally plentiful farther south, in the Copper River and Susitna River basins.

Game.—The list of game animals suitable for food or bearing fur in the Broad Pass region includes moose, caribou, sheep, bear, wolverine, and fox. Among the smaller fur-bearing animals are otter, mink, marten, muskrat, the so-called ermine (weasel), and the "parka squirrel." Ptarmigan are the chief game birds, although a few grouse are found in the timbered areas. Trout and grayling are plentiful in many of the clear-water streams and the lakes.

The Indians of the upper Susitna spend a large part of the year hunting on Jack River and on the Yanert Fork of Nenana River. These two localities are considered the choice hunting grounds of the region, and Yanert Fork is the better of the two. Formerly the lower Susitna natives also hunted in the Broad Pass region, coming into it by way of Chulitna River or the valley leading northeastward from the head of Indian Creek. Broad Pass itself seems to have been the northern limit of their territory.

Before the discovery of gold on Valdez Creek the upper Susitna natives depended on the country for most of their food and clothing. Valdez Creek was a favorite hunting ground; in fact, the native name for Valdez Creek (Galena, accented on the first syllable) signifies a river where game abounds. After mining began, however, large game practically disappeared from the creek and also from the head of the Susitna, where both moose and caribou were formerly common.

Moose are now found occasionally in the upper Chulitna Valley, and they sometimes come up Susitna River from the lowlands west of Copper River and travel between the Susitna and Chulitna rivers through the Nenana Valley. In Chulitna Valley they are rarely disturbed by white men.

Caribou travel over nearly all of the region and may be seen in almost any part of it at some time during the year, but according to the miners of Valdez Creek they rarely come to the Susitna flats of late years. Yanert Fork, Jack River, the valley between Yanert Fork and Nenana River and the vicinity of Broad Pass are favorite feeding grounds of the caribou.

Mountain sheep, within the mapped area, are almost restricted to the Yanert Fork of Nenana River and to the eastern branches of Chulitna River. It is not understood why they are more numerous on the north slopes of the Alaska Range than on the south slopes, but no sheep were seen on the south side of the range except on the branch of the Chulitna heading against the upper part of Jack River, where they appear to be numerous.

Several brown bears were seen on Yanert Fork and Nenana River members of the Survey parties, but the evidences of bears were

not plentiful in other parts of the region. Two wolverines were surprised one morning on the Middle Fork of Susitna River, an uncommon sight, for the wolverine usually manages to keep himself hidden in summer. Foxes were seen in different parts of the region, among them one black fox. The other fur-bearing animals that have been mentioned, except squirrels, which are numerous and widely distributed, are known from the skins in the possession of the white men and the natives.

Ptarmigan are abundant in all the Broad Pass region. They frequent the willow thickets in the upper parts of valleys and on hill slopes. Their peculiar cry was often heard during the summer, especially in the early morning. During the nesting season several broods of chicks were found almost every day.

Two kinds of fish, grayling and trout, abound in the clear waters of this region. Salmon does not ascend Susitna River above the falls a few miles east of Indian Creek—at least it is so reported by prospectors—and no salmon were seen in the upper Susitna by the Survey parties. It was not learned whether they ascend Chulitna River or whether there, too, they are prevented from doing so by some natural obstruction like the falls of the Susitna.

Most of the grayling caught during the summer were taken from deep, sluggish streams. They were large and very dark, almost black in color. The meat was white or pinkish and rather dry. Butte Creek, Deadman Creek, and Jack River are good grayling streams. Their waters are clear, for their sources are not glacial; fish avoid the milky glacier water.

Trout were taken from the clear-water streams but are most abundant and reach their greatest size in the deep lakes, such as Butte Lake, which has long been known by the Indians as good fishing water. A large trout from Butte Lake is reported to have weighed over 30 pounds. The tackle commonly used for these fish is a heavy hand line and a large hook baited with the tail of a grayling.

Population.—The Broad Pass region has no permanent settlements, either of white men or of Indians. About 25 whites were engaged in mining on Valdez Creek in 1913. These men stay on the creek for half the year and all but one or two go to the coast or out to the States in the fall. They, together with the prospectors of the Wood River district north of the Alaska Range, constitute the white population nearest the Broad Pass region.

The Indians who hunt on Jack River and Yanert Fork also have their cabins on Valdez Creek. Formerly they lived in the vicinity of Tyon River and the big bend of the Susitna, but within the last few years have moved to Valdez Creek and established themselves there in order to trade and obtain the white man's supplies more

easily. Some of the miners on Valdez Creek take in extra supplies of groceries, tobacco, and ammunition for this purpose. Before the discovery of gold on Valdez Creek the Tyon River Indians were more independent and saw much less of white men than now. They made yearly trading expeditions to Cook Inlet and carried their contributions to the Russian Church or took their children to be christened by its priests. Practically all their supplies and clothing, except tea, sugar, ammunition, and a little cloth were obtained by hunting or fishing. The upper Susitna and the headwaters of Nenana River, together with the immediate vicinity of the Tyon Lakes and Tyon River, where the chief lived, belonged in their hunting grounds.

At present the natives stay in their cabins on Valdez Creek until early July and then leave for the hunting grounds to spend the summer and kill game for the winter. They start out with a small canvas for shelter and a few supplies like tea and sugar to supplement the diet of meat, fish, and berries that will constitute their chief food supply until they return.

Some of the younger men are employed by the miners on Valdez Creek for different kinds of work and are found to do fairly well except in the matter of attendance. It often happens that they are absent when most needed, even after they have promised faithfully to be on hand. Experience has taught the miners that Indians will not work contentedly unless they are given occasional opportunities to spend a day or two in hunting or fishing. Some of the younger men are inclined to gamble away their wages or to avoid work in the hunting season, feeling that inasmuch as most of the money they earn goes into the general family fund rather than into their own pockets, they receive no particular benefit from it. The older men are less disposed to work, a thing they have never been trained to do, but are more careful with the money they receive. They have been allowed to take what gold they can get by panning on certain of the Valdez Creek claims and obtain a considerable amount of the white man's supplies with the proceeds.

GENERAL GEOLOGY.

STRATIGRAPHY.

Geologic Map and Summary of Formations.

The distribution of geologic formations in the Broad Pass region is represented on the geologic map (Pl. II, in pocket) accompanying this report. Inasmuch as the field investigation was merely a reconnaissance, this map shows only the broad general features of formation distribution and lacks the detail that a longer period of work would have brought out. Yet it is believed that some of the forma-

A. TYPICAL EXPOSURE OF THE LIMESTONE AND ARGILLITE FORMATION (MESOZOIC?) SOUTHWEST OF NENANA GLACIER.

B. VIEW NORTHWARD ACROSS NENANA GLACIER.

Shows a lateral overflow of the glacier and vertical jointing of the granite mountains in the background.

tion boundaries are shown with almost as much accuracy as the scale of mapping permits. The earlier map by Brooks[1] has been used in extending the colors of the present map from the canyon a few miles below the Jack River on the Nenana to the mouth of Yanert Fork. This part of the region was not visited by the geologic party in 1913, although it was surveyed topographically by Mr. Bagley.

The geology of the Broad Pass region may be outlined as follows: The rocks consist chiefly of folded and more or less metamorphosed sediments intruded by large bodies of granular igneous rock and associated with extensive lava flows. The sediments include schist, slate, shale, sandstone, conglomerate, and limestone, all of which show metamorphism in some degree, expressed chiefly by schistosity and silicification, although parts of the oldest as well as of the youngest appear to be little altered. They range in age from Devonian to Eocene and possibly later Tertiary. All the consolidated sedimentary formations show folding and faulting, and some of the more recent show almost as much alteration as the oldest, so that metamorphism is not everywhere a safe guide in determining their relative ages.

The granitic rocks intruded into the sedimentary formations include granite, quartz monzonite, quartz diorite, and olivine gabbro. The granite is locally associated with coarse granite porphyry and with rhyolitic, trachytic, and andesitic lavas. Basaltic and andesitic lavas with tuffaceous beds having no evident connection with the granular intrusives are also present. The igneous rocks range in age from Jurassic or earlier to post-Eocene.

Much of the hard rock of the Broad Pass region is buried under unconsolidated deposits that include sand, gravel, morainal débris, and unsorted rock waste from many sources. This whole region has been profoundly glaciated and exhibits all the common evidences of glaciation in mountainous and piedmont areas. (See Pls. III, *B*, p. 8; IV, *A* and *B*, p. 12; and VIII, *B*.)

The stratigraphic positions of the sedimentary formations represented on the map are shown in the following table:

Geologic column of the Broad Pass region.

Quaternary:
1. Stream gravels, sands, silts, and unsorted rock waste.
2. Glacial gravels and morainal deposits.

Tertiary:
1. Shale, sandstone, and conglomerate, more or less indurated.
2. Cantwell formation, consisting of massive conglomerate, in part schistose, and finer-grained clastics, mostly sandstone, with intercalated beds of graywacke, argillite, carbonaceous shale, and slate carrying leaf impressions of Eocene age.

[1] Brooks, A. H., The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, pl. 9, 1911.

Undifferentiated Mesozoic (?):

Slates, argillites, graywacke, and thin-bedded limestone, differing widely in closeness of folding and degree of metamorphism; more or less silicified in part.

Jurassic (?):

Closely folded, dark-blue slate with beds of conglomerate, graywacke, and impure limestone, more or less altered; well exposed on upper Jack River and in the mountains south of Broad Pass.

Triassic (?):

1. Slate with intercalated beds of coarser sediments (graywacke, arkose, and similar rocks), closely folded and in part schistose (Upper Triassic?).
2. Basic lava flows with tuff beds.

Devonian:

Limestone, locally silicified and metamorphosed, with slate and mashed conglomerate (Middle or Upper Devonian).

Paleozoic Rocks.

DEVONIAN ROCKS.

CHARACTER AND DISTRIBUTION.

A belt of rocks consisting of limestone, slate, and a minor amount of altered conglomerate is exposed along Jack River in the lower hills and mountains that lie between the eastward-trending Nenana-Chulitna Valley and the main ridges of the Alaska Range. This belt is about 5 miles wide in this vicinity and lies parallel to the axis of the range, extending almost directly east and west. From Jack River it was traced eastward nearly to the Nenana Glacier and westward for 5 or 6 miles. Its continuation 10 miles or more farther west is inferred from the appearance and form of the mountains north of Broad Pass.

The limestone appears in large exposures, locally forming whole ridges, and is more or less metamorphosed in all places where it was examined, yet in some places is not altered enough to destroy or even to injure the fossils contained in it. The most thorough alteration observed is that by silicification, which in places has gone so far as almost to hide the identity of the rock. Recrystallization of the calcite into marble has not occurred extensively, if at all, not even near intrusive masses, where it might well be expected, although the metamorphism in such places is more pronounced than elsewhere.

Slates and conglomerate are associated with the limestone, the conglomerate being mashed and in places schistose, and these rocks have been closely folded and for the most part stand at high angles. The bedding planes are not recognized easily, but the general strike of the beds is indicated by the course of the limestone ridges and by that of the belt itself.

The Devonian rocks are intruded by granular igneous masses, which have probably caused the silicification of the limestone.

AGE AND CORRELATION.

The rocks that have just been described are classed together on account of their mutual structural relations and their positions with reference to adjacent formations. Fossils were found in a limestone bed on the east side of Jack River at the point where that stream turns westward after impinging on the end of a low ridge north of the old Nenana-Chulitna river valley. At this locality a vertical bed of limestone is included between walls of slate and in one place mashed conglomerate. The fossils collected were identified by Edwin Kirk, who pronounces them Devonian, to which period the limestone is therefore referred. Kirk's report follows:

Nos. F13 AP36; F13 AM1. Locality, right bank of Jack River, about 8 miles above mouth.

Cladopora sp.	Pleurotomaria sp.
Cyathophyllum sp.	Euomphalus sp.
Syringopora sp.	Tentaculites sp.
Diphyphyllum ? sp.	Orthoceras sp.
Martinia cf. maia (Billings).	Modiomorpha sp.
Reticularia ? sp.	Leperditia sp.
Loxonema sp.	Proetus (same as that referred by Kindle to *haldemani* Hall).
Naticopsis sp.	

Owing to the rather poor preservation of most of the specimens and to the fact that in large part the fossils represented are undescribed, it is not possible to give specific determinations. The material renders possible, however, a fairly accurate age determination, and a rough correlation with other deposits in Alaska may be made.

This collection probably represents the same general stratigraphic horizon as that described by Brooks[1] in his report on the Mount McKinley region. Similar faunas have also been collected on the south side of Freshwater Bay, Long Island, and on Porcupine River. Identical species occur in this collection and in the collections made by Kindle[2] in the Salmon Trout limestone on the Porcupine. It is interesting to note that an apparently identical fauna has been found on the southern shore of Great Slave Lake. I have examined a small collection from this locality and it contains identical species.

The general stratigraphic horizon of the material is probably upper Middle Devonian, or else lower Upper Devonian.

Fossils were not found in any of the other rocks mapped as Devonian, and future work may possibly show that some of these beds belong to other systems than the Devonian. Possibly, too, some of the rocks in groups referred to later systems may be Devonian, but it is not believed that any great error of this kind has been made. Rocks of nearly the same character and age are found in the Alaska

[1] Brooks, A. H., The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, p. 78, 1911.

[2] Brooks, A. H., and Kindle, E. M., Geol. Soc. America Bull., vol. 19, pp. 277–291, 1908.

Range southwest of Broad Pass, notably near the head of Kuskokwim River.[1] Such rocks have also been mapped between Yukon and Tanana rivers.[2] Devonian rocks have not been observed in the Alaska Range east of Susitna River, but they have been found[3] in the Nutzotin Mountains.

Mesozoic Rocks.

Two kinds of rocks in the Broad Pass region are tentatively referred to the Triassic. They are the basaltic lava flows in the southeastern part of the region and the slates that adjoin the lava flows on the north. Neither of these formations is known definitely to be of Triassic age; no fossils have been collected from them, and their provisional assignment to the Triassic is based on seeming structural relations and other considerations.

TRIASSIC (?) LAVAS.

CHARACTER AND DISTRIBUTION.

The lavas that are here tentatively assigned to the Triassic form the ridge of mountains south of Butte Creek in the southeast part of the mapped area. These mountains form the western end of a minor range of mountains that flanks the Alaska Range between Susitna River and the vicinity of Gulkana Lake. This range is made up principally of basaltic lava flows, with which are associated andesitic flows and beds of water-laid tuffaceous material.

The lava flows south of Butte Creek were examined carefully at only one locality, south of Wickersham Creek, so that it is not possible to say with certainty that they correspond in all respects to the similar rocks east of Susitna River, but no reason is known for assuming that they do not. At the locality near the mouth of Butte Creek the mountains are composed of thick flows of basalt that has andesitic phases and that is in part amygdaloidal. Specimens from the outcrops of the rock are dark greenish, have a medium to fine-grained texture, and contain feldspar, pyroxene, and more or less olivine. Joint planes and slickensided surfaces are abundantly developed in the lavas. Loose blocks on the talus slopes show coarser phases of the rock than were seen in the outcrops. Some of this material has the appearance of gabbro, and some is amygdaloidal, the amygdules having maximum diameters of 1 inch and consisting of olivine, surrounded in places with a zone of zeolitic material. Serpentine is a common alteration product in the basalts, and

[1] Brooks, A. H., The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, pl. 9, 1911. Maddren, A. G., U. S. Geol. Survey Bull, 410, pp. 50–51, 1910.

[2] Brooks, A. H., op. cit. Brooks, A. H., and Kindle, E. M., op. cit.

[3] Capps, S. R., Mineral resources of the Chisana-White River district, Alaska: U. S. Geol. Survey Bull. 622, pp. 189–228, 1915.

at many places appears as small veins. Fine-grained tuffs and tuffaceous conglomerates were not seen at this place. They are well developed south of the Roosevelt Lakes and at other places east of Susitna River studied by the writer in 1910.[1] By careful search tuffaceous beds may be found in the mountains south of Butte Creek.

The stratigraphic position of the basaltic lavas with reference to the slates north of Butte Creek has not been clearly determined, and the geologic conditions in this locality are unfavorable to exact determination, for the lavas and slates are separated by the wide valley of Butte Creek, and the contact of the formations is hidden under gravel deposits. If the slates north of Butte Creek can properly be correlated with the Triassic (?) slates and limestones south of the Roosevelt Lakes, the basalts may underlie these slates, for the best evidence indicates that they underlie the slates in the Roosevelt Lakes district.[2] On the other hand, the lava beds south of Butte Creek have a gentle southeasterly dip at the locality visited, which does not appear to corroborate the evidence found in the Roosevelt Lakes district, and suggests either a fault between the lavas and slates or a reversal of dip of the lava flows in the part of the Butte Creek valley floor that is buried under the gravel deposits. The inclination of the lava beds, however, furnishes a suggestion as to the thickness of the flows exposed in this locality. A calculation based on the assumption that the gentle dip remains fairly constant in the northern part of the mountains south of Butte Creek and on the known elevation of the highest mountains gives a thickness of 3,500 feet for the flows in this locality.

As has been stated, the lava flows at a number of places east of Susitna River are associated with argillites, tuffs, and tuffaceous conglomerates, indicating that repeated outpourings of lava were separated by intervals of time in which water-worn material as well as angular material produced during volcanic outbursts was deposited. Possibly some of the lavas may have been poured out and cooled under water, but of this no direct evidence was obtained.

AGE AND CORRELATION.

The age of the basaltic lavas has been determined from evidence afforded by other regions and is not certainly known. Near the mouth of Eureka Creek, a tributary of Delta River, the lavas seem to overlie Carboniferous sediments.[2] In the district between Clearwater Creek and the Roosevelt Lakes the lavas seem to overlie sediments of probable Upper Triassic age. In both these places the uncertainties arise not from the present positions of the rocks, but

[1] Moffit, F. H., Headwater regions of Gulkana and Susitna rivers, Alaska: U. S. Geol. Survey Bull. 493, p. 29, 1913.
[2] Idem, p. 30.

from difficulties of interpretation caused by folding and faulting. The evidence cited indicates that the basaltic lavas of the Gulkana-Valdez Creek region were extruded either in late Carboniferous or early Mesozoic time, before the Upper Triassic sediments were deposited.

In the region south of that under discussion most of the northern half of the Talkeetna Mountains is made up of rocks, largely volcanic, which are described by Paige and Knopf[1] as consisting of andesitic greenstones, dacites, rhyolites, and associated tuffs. Brooks[2] correlates these rocks with the Skwentna group of Spurr. Their Lower Jurassic age is indicated by fossils[3] collected from similar tuffs in the Matanuska Valley. Lithologically the lava flows south of Butte Creek resemble the flows to the east more than those of the northern Talkeetna Mountains, but the nearness of these mountains and the fact that Lower Jurassic time is known to have been characterized by volcanic activity in this part of Alaska make it necessary to consider the evidence carefully. The basalts of Butte Creek bear a close resemblance to the Nikolai greenstone of Chitina Valley and to greenstones exposed in some other parts of the Wrangell Mountains. The Nikolai greenstone is a great series of basaltic lava flows, at least 4,000 feet thick in the Nizina district. Its upper age limit is determined by the Chitistone limestone, which overlies the greenstone and was deposited in Upper Triassic time.[4] The lower age limit is unknown, but evidence has been presented tending to show that it can not be below the uppermost part of the Pennsylvanian, in which case the Nikolai greenstone is of late Carboniferous or Triassic age. Some reasons appear, therefore, for correlating the Nikolai greenstone and the basaltic flows of the Gulkana-Valdez Creek, region, but no evidence has been found in either region which would warrant a definite assignment of the lavas to either the Carboniferous or Triassic period. In discussing the geologic column of the upper Susitna-Gulkana district the lava flows were described as of Carboniferous or later age,[5] but the uncertainty concerning the relative stratigraphic positions of the lava flows and slates on Butte Creek makes it advisable here to include the lavas among the Mesozoic formations rather than to assign them to the Carboniferous.

[1] Paige, Sidney, and Knopf, Adolph, Geologic reconnaissance in the Matanuska and Talkeetna basins, Alaska: U. S. Geol. Survey Bull. 327, p. 16, 1907.

[2] Brooks, A. H., The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, p. 85, 1911.

[3] Martin, G. C., and Katz, F. J., Geology and coal fields of the lower Matanuska Valley, Alaska: U. S. Geol. Survey Bull. 500, pp. 29–32, 1912.

[4] Moffit, F. H., and Maddren, A. G., Mineral resources of the Kotsina-Chitina region, Alaska: U. S. Geol. Survey Bull. 374, p. 27, 1909. Moffit, F. H., and Capps, S. R., Geology and mineral resources of the Nizina district, Alaska: U. S. Geol. Survey Bull. 448, p. 23, 1911.

[5] Moffit, F. H., Headwater regions of Gulkana and Susitna rivers, Alaska: U. S. Geol. Survey Bull. 498, p. 22, 1913.

TRIASSIC (?) SEDIMENTS.

CHARACTER AND DISTRIBUTION.

The sedimentary rocks tentatively assigned to the Triassic consist prevailingly of dark-blue and black slates, but include interstratified beds of arkose and graywacke. Although no section of these rocks was measured, their thickness is probably considerable, possibly amounting to several thousand feet. They are closely folded and show different degrees of metamorphism. Locally the argillite and arkose have been changed to phyllite and schist. Dikes of granitic and andesitic rock cut the beds and large masses of granite and diorite invade them. The Triassic (?) sediments form a belt 5 or 6 miles wide, separated from the lava flows on the south by the valleys of Butte Creek and the eastern fork of Watana Creek. They are regarded as a westward extension of the Triassic slate exposed in the Valdez Creek district.[1]

Dark-blue or black slate is the predominating rock of this group. Most of it has well-developed slaty cleavage, and splits with a smooth plane surface. There is some variation in the perfection of cleavage, however, for in places the rock shows little tendency to split and in others it splits with a more or less uneven crinkly surface. With increase in size of the constituent particles the slate grades into arkose or graywacke. Such gradations are most noticeable where the strike of the beds is crossed, yet if individual beds are traced along the strike for a considerable distance the change in coarseness or fineness of grain would probably be seen to take place in that direction also.

The coarser sediments are distributed through the slate in comparatively thin beds. They are finely granular and dark gray. Most of them are made up of small fragments of quartz, feldspar, and dark minerals of several kinds, but in places the dark minerals are lacking or are present only in small amount, so that this phase of the rock should be called arkose rather than graywacke. Locally the graywacke beds have become schistose. A specimen of schistose graywacke collected near Butte Creek was found under the microscope to contain grains and granulated areas of quartz interlaced with sericite. Associated with the quartz and sericite are subangular fragments of feldspar, both orthoclase and plagioclase, and a few shreds of biotite and altered hornblende. The quartz shows undulatory extinction.

It is not yet possible to determine even approximately the thickness of this group of beds of slate and graywacke, for pressure has

[1] Moffit, F. H., Headwater regions of Gulkana and Susitna rivers, Alaska: U. S. Geol. Survey Bull. 498, pl. 2, 1912.

thrown them into close folds and faulting has still further complicated their structure. The observer crossing their strike probably meets the same bed several times, yet beds of this group doubtless measure hundreds or, more likely, thousands of feet.

The pressure that folded these beds gave rise to other metamorphic changes, which, however, are not constant throughout the formation, as may be seen in the lack of cleavage in some of the rocks and the schistose nature of others. The folding of the beds was accompanied also by more or less faulting, but how important a part faulting plays in the structure of the beds and their relation to other formations is not known.

Quartz veins were developed locally in the slates and graywackes. They show little or no mineralization, but may contain a small amount of gold, for the stream gravels within the slate area commonly yield a little placer gold when panned.

A wide variation in the strike of the beds was noticed. The compass readings range from N. 20° E. to N. 80° E., but in general are about N. 70° E., which is the trend of the belt itself. There is some difference, however, between the prevailing strike of the beds in the eastern and western parts of the mapped area, for in the western end of the belt the strikes become a little more southerly. The prevailing dip of the bedding is northwestward and is steep, about 80°. The observations suggest a series of close folds, slightly overturned to the southeast and having the same general trend as the Alaska Range in this region.

The exposed Triassic (?) sediments are separated from the lava flows on the south by a wide gravel-floored valley and are bounded on the north either by intruded granitic rocks or by gravel deposits, so that no contact between them and older or younger sedimentary formations was seen. Some evidence has been advanced to show that the Triassic sediments of Coal Creek and Clearwater Creek in the Valdez Creek district rest unconformably, either by deposition or because of faulting, on the lava flows.[1] If the unconformity in that district is one of deposition, then the conditions are different from those in the Chitina Valley, where in many places Triassic sediments of the same age as those of Coal Creek rest conformably on the underlying lava flows and give no apparent evidence of an erosion interval between the two formations. The known facts clearly do not warrant a definite statement regarding the relation of the Triassic sediments to the older formations. If the belt of lava flows crossing the Valdez Creek and Broad Pass regions proves to be of Carboniferous age, the Triassic (?) sediments probably lie on them unconformably. On the other hand, if the lavas are of Triassic

[1] Moffit, F. H., Headwater regions of Gulkana and Susitna rivers, Alaska: U. S. Geol. Survey Bull. 498, pp. 30, 31, 1912.

age, then a similar relation of sediments to lava flows as that in the Chitina Valley may be found.

The slate and graywacke of this group has been intruded by dikes of granite and, less commonly, of andesitic rock. Small pegmatite dikes were seen in mashed and partly silicified slates at one place near the monzonite intrusion north of Wachana Creek (Pl. II, in pocket). The slate here is extensively mineralized with pyrite and probably carries a little gold. A mile to the southeast, at the border of the monzonite mass, the metamorphosed slates contain dikelike intrusions of fine-grained biotite-hornblende granite, dioritic phases of the same rock, and rhyolite porphyry. A large dike of diorite crosses Wickersham Creek about 3 miles from the mouth, and as it is more resistant than the inclosing slates, it has formed a waterfall. These dike rocks and the large intrusive masses of granite and monzonite, with which they are probably closely connected, will be discussed in the section on igneous rocks.

AGE AND CORRELATION.

The slate and graywacke formation immediately north of Butte Creek is the westward continuation of a formation well exposed east of Susitna River in the mountains south of Valdez and Roosevelt creeks, about the head of Clearwater Creek, and on the head of West Fork of Maclaren River. Fossils collected from limestones and shales in the lower part of this formation show that the beds were laid down in Upper Triassic time and are equivalent in age to the Chitistone limestone and McCarthy shale of the Chitina Valley[1] and to the Triassic limestone of the Nabesna River region.

The Upper Triassic sedimentary deposits of the Chitina Valley, the Chitistone limestone and McCarthy shale, have a thickness of at least 5,500 feet in the Nizina district. The McCarthy formation, which overlies the limestone, has a thickness of not less than 2,500 feet and is composed almost entirely of shale or, more accurately, of slate, except a comparatively small part at the base, which is made up of thin alternating beds of limestone and shale. The known Triassic rocks of the Nabesna district are limestone, but the limestone is associated with a great thickness of Mesozoic slate, graywacke, and conglomerate that is in large part of Upper Jurassic age, but may perhaps include Triassic deposits also. Triassic deposits are not known in the Talkeetna Mountains, but Upper Triassic sediments are well developed on Kenai Peninsula and in the Alaska Peninsula.[2]

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[1] Moffit, F. H., and Capps, S. R., Geology and mineral resources of the Nizina district, Alaska: U. S. Geol. Survey Bull. 448, pp. 21, 28, 1911. Moffit, F. H., and Knopf, Adolph, Mineral resources of the Nabesna-White River district, Alaska: U. S. Geol. Survey Bull. 417, p. 27, 1910.

[2] Stanton, T. W., and Martin, G. C., Mesozoic section on Cook Inlet and Alaska Peninsula: Geol. Soc. America Bull., vol. 16, p. 410, 1905.

JURASSIC (?) ROCKS.

CHARACTER AND DISTRIBUTION.

The rocks tentatively referred to the Jurassic are typically exposed in the mountains south of Broad Pass and west of Jack River. These mountains are made up of closely folded dark-blue and black slates interbedded with graywacke and conglomerate. Impure limestone, more or less altered, is interstratified with the slate and graywacke east of Jack River, but was not seen at Broad Pass. The thickness of the beds is unknown, but is probably several thousand feet. The relation of the group to older formations, too, has not been determined, yet is believed to be that of unconformity. In addition to being folded, faulted, and more or less metamorphosed these sedimentary deposits are intruded by large masses of granular igneous rock of granitic and monzonitic character, with which are associated rhyolitic lavas and coarse granite porphyry.

Slate is the predominating rock throughout the group within the region mapped. The conglomerate, graywacke, and limestone, however, are not equally developed in all parts of the area assigned to the Jurassic. Limestone is more common in the eastern part and graywacke and conglomerate in the western part, there being apparently a progressive increase in the coarseness of the sediments from the east toward the west in this area.

The slate for the most part is dark blue, but in places is black or dark gray. Locally it is carbonaceous. It shows different degrees of metamorphism, ranging from almost unaltered argillite to phyllite or schist. Much of it has a well-developed slaty cleavage, which is prevailingly parallel to the bedding but crosses it in places, probably in the bends of the folds. A much smaller proportion of the rocks called slate might possibly be described more accurately as schist. By an increase in size of the constituent particles the slate grades into graywacke.

The conglomerate occurs in beds of relatively hard, dense rock, made up of well-rounded water-worn fragments of silicified slate, quartz, chalcedony, and altered lava, set in a groundmass of similar material cemented with quartz. It is dark gray and in places has undergone considerable metamorphism, the pebbles being stretched and the whole rock assuming some of the characteristics of schist. The pebbles are commonly small, ranging from one-fourth inch to 1 inch in diameter in most beds, yet reaching a diameter of 2 inches in others. On account of its denseness, hardness, and the large amount of quartz which it contains the conglomerate does not weather readily but breaks into angular blocks and fragments that resist chemical alteration yet are readily attacked by temperature

changes and ice. Jointing plays a prominent part in the breaking down of the conglomerate beds.

The conglomerate, like the slate, grades into graywacke, all three types probably having derived their constituents from the same source in some near-by land mass. Few of the conglomerate beds, so far as observed, exceed 20 feet in thickness.

The graywacke is light gray to dark gray, and is made up of fine angular or subangular grains of quartz, feldspar, and dark-colored rock fragments. A hand specimen of it shows a rough surface and suggests a very coarse slate but differs from slate in its poorer cleavage and in the size of the constituent particles, which are readily distinguished by the eye alone. Isolated fragments of slate from an inch to several inches in length are sometimes seen on joint planes that cross the bedding of the graywacke. They attract notice through the contrast of their dark color and large size as compared with the particles of the fine-grained groundmass in which they lie. Locally the graywacke, like the slate and conglomerate, becomes somewhat schistose. The microscope shows that quartz fragments predominate over feldspar among the constituents and that sericite and chlorite are present. Feldspar of both the orthoclase and plagioclase varieties is also present. Among the rock types represented by fragments sufficiently large to be identified are slate, which is the most abundant, quartzite, and two or more kinds of igneous rock. Those beds of graywacke that became schistose lost much of their granularity and show the development of micaceous minerals such as sericite and chlorite. Undulatory extinction and shattering of the quartz grains are evidences of the pressure to which the rock has been subjected. The schistose phases of the graywacke, nevertheless, can usually be recognized as being derived from rocks like the more massive, less altered phases. The graywacke beds exhibit great variability in thickness, ranging from a few inches to a thousand feet or more. Study of the graywacke makes it evident that this rock differs from the slate and conglomerate with which it is interbedded chiefly in the size of the particles that compose it and that it represents the accumulation of fine undecomposed waste derived from a land mass not far distant, where the processes of degradation were proceeding rapidly.

Limestone forms thin beds interstratified with the slate and is least common in those parts of the group where graywacke and conglomerate are most abundant. It was not seen west of Jack River but may be present. The rock is impure and is dark gray or black, so that at a little distance it is not distinguishable from the slate. In the vicinity of intrusive rocks it has been silicified and impregnated with pyrite.

The thickness of this group of sedimentary beds is not known. It is evidently great, whatever interpretation may be placed on the structure of the group, and must be thousands of feet. The folding of the strata and the difficulty of determining reference beds made it impossible in the time available either to form a definite idea of the thickness of the beds or to make certain of their larger structure, including their relation to the older underlying formations. They probably lie in a succession of close folds, slightly overturned, so that the axial planes dip southward. The strike of the beds ranges from N. 50° E. to N. 70° E. and is approximately parallel to the axis of the Alaska range in this region. As has been pointed out the forces that gave rise to folding also produced a cleavage in the finer grained clastics that is more or less well developed in accordance with the character of the rock affected and with other conditions. Metamorphism, of which slaty cleavage is only one manifestation, although perhaps the most noticeable, is slight in some places, but proceeded so far in others that new minerals and new textures such as are seen in the schistose varieties of the slate, graywacke, and conglomerate, were introduced. Not much faulting was observed. This seeming rarity of faulting is probably not real and is due to the character of the rocks and the difficulty of recognizing faults rather than to their absence.

Stringers and veinlets of quartz cut the beds but so far as observation showed are not accompanied by notable mineralization.

The base of this group of slate, graywacke, and conglomerate was not observed and its stratigraphic position with reference to underlying formations was not determined. It seems probable, however, that if the group is correctly referred to the Jurassic its relation to the near-by Devonian formations is one of depositional unconformity, for rocks of the intervening periods are not recognized in this vicinity although they are known in the region.

Granitic intrusive masses of large size lie adjacent to the group of slate, graywacke, and conglomerate along the southern border. In addition, the sedimentary beds of this group are intruded by dikes of rhyolite porphyry. These dikes, however, are not common, and seemingly are offshoots of the larger intrusive masses. No basic dikes were found.

Between the head of Seattle Creek and Jack River the slates and graywackes lie adjacent to an area of acid lavas which also are believed to be directly related to the large intrusive masses of granite. The igneous rocks are considered more fully on pages 54–65.

The group of sedimentary formations just described is well exposed southeast of Broad Pass in the vicinity of Jack River. According to Eldridge[1] it extends southwestward from Jack River to

[1] Eldridge, G. H., A reconnaissance in the Sushitna basin and adjacent territory, Alaska, in 1898: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, p. 15 and map No. 3, 1900.

Indian Creek and continues thence down Susitna River to a point about 15 miles above the mouth of Chulitna River. He gave it the name "Sushitna slates" and describes the beds as quartzitic and varying in coarseness from fine-grained to granular. He found the rocks extensively sheared, the shearing being accompanied by the production of a partial schistose or slaty structure, and noted that locally there had been a marked crumpling of the strata and a formation of numerous quartz veins, many of which contained pyrite. From this description limestone evidently forms little if any part in the group where Eldridge studied it.

These beds extend northeastward from Jack River, forming the front of the mountains south of the old Nenana Valley for about 10 miles, but giving way to gravels and igneous rocks a few miles west of the mouth of Wells Creek. Their continuation east of Wells Creek and north of Nenana River is in doubt, although the mountains southeast of Nenana Glacier, mapped as undifferentiated Mesozoic (?) (Pl. II, in pocket), may include some of this group. The mountains of this vicinity consist of slate and limestone, commonly occurring as thin beds interstratified with slate and forming a much larger proportion of the whole than the similar beds in the mountains east of Jack River and south of the Nenana.

The group of Jurassic (?) sedimentary beds that has been described indicates sedimentation under conditions that were unstable and changing with comparative rapidity, as is shown by the kinds of material laid down, the thinness of the beds, and the change, many times repeated, from conglomerate to graywacke, from graywacke to slate, from slate to limestone, or the reverse. The beds probably accumulated in comparatively shallow water near the shore of a land mass, where streams brought in a variety of material that underwent change in the manner of its deposition and in part at least accumulated as delta and flood-plain deposits.

AGE AND CORRELATION.

The sedimentary formations just described are referred tentatively and without the evidence of fossils to the Jurassic, as it is believed that they are to be correlated with rocks of known approximate age in near-by districts.

Previous work by Eldridge, Brooks, and Capps in the Susitna basin has shown that a belt of folded and more or less metamorphosed sediments extends along the flank of the Alaska Range from Skwentna River to Jack River. This belt may contain rocks of two or more periods, but it consists essentially of slate and graywacke in variable proportions with which are associated quartzite, sandstone, and limestone in minor amounts.

On the lower part of Kahiltna River, between Skwentna and Yentna rivers, Brooks found a belt of rocks "composed chiefly of black carbonaceous slate and phyllite, with some heavier beds of fine graywacke and grit."[1] In this belt the foliated rocks are much more abundant than the massive ones. Brooks refers all these rocks to the Paleozoic, but says that "it is by no means impossible that they may be Mesozoic."

Northwest of this belt is another belt of similar rocks, about 30 miles wide, the Tordrillo formation, which "consists of a series of closely folded and faulted grits, sandstone, and fine conglomerate, together with argillite and a few layers of limestone."[2] Massive grits and sandstone predominate in the lower part of the formation; argillite with subordinate sandstone members and a few limestone layers makes up the upper part. Middle Jurassic fossils were collected from beds of the Tordrillo formation. On the west the Tordrillo formation gives rather definite evidence of resting unconformably on the slates and phyllites of the Tonzona group (Devonian or Silurian). The Tordrillo formation also overlies the Paleozoic (?) sediments to the southeast and thus forms a broad synclinorium of closely folded Middle Jurassic sediments. Large masses of granite and granodiorite and numerous dikes and sills of monzonite and rocks of kindred type are intruded into the Tordrillo formation.

Capps found a series of slates and graywackes extending northeastward from Yentna River to the Chulitna.[3] He regards these beds as the northeastward continuation of Brooks's "undifferentiated Paleozoic" sediments of the Kichatna, and describes them thus:

> They consist chiefly of black to gray slates and phyllites, in many places carbonaceous, and beds of graywacke, which range from fine-grained to coarse gritty rocks. In some places the rocks are massive, with argillites instead of slates, but the foliated types are much more widespread than the massive types. It is difficult to estimate just what proportion of the whole series is formed by the graywacke beds. Many sections show great thicknesses of the slaty phases, with very little graywacke present. At other localities the graywackes preponderate, occurring in thick massive beds that show little foliation or schistosity and that are often mistaken by the miners for fine-grained dike rocks, which they closely resemble.

Capps traced these beds to Tokichitna River, within 10 miles of the slate-graywacke area east of Susitna River described by Eldridge, and believed that a correlation of the rocks of the two areas was justified.

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[1] Brooks, A. H., The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, p. 67, 1911.

[2] Idem, p. 87.

[3] Capps, S. R., The Yentna district, Alaska: U. S. Geol. Survey Bull. 534, pp. 24, 25, 1913.

Eldridge traced the Susitna slate from a point opposite the mouth of Tokichitna River to Jack River, and says of it:[1]

> The beds are essentially quartzitic, varying in coarseness of material from an extremely fine homogeneous rock to one of granular structure. In addition to quartz there are occasional orthoclase, plagioclase, biotite, muscovite, scattered grains of iron oxide, and minute fragments of slate—apparently of the same nature as the fine-grained slates of the series itself.

It is evident from this description and from his field notes that Eldridge included graywacke ("pyroclastic diorite," as he called it) under the term slate. The field notes also state that he saw no difference between the rocks in the vicinity of Indian Creek and Jack River except for some intrusive rocks near the head of Jack River.

A comparison of the formations in the districts described by Eldridge, Brooks, and Capps, and more particularly a study of the geologic maps made by them, appears to confirm Capp's correlation of his slate-graywacke series with the rocks of the lower Kichatna River and with Eldridge's Susitna slate. If this correlation is made it is necessary either to consider the slate, graywacke, and conglomerate formations of Jack River as Paleozoic or to present evidence in favor of the possibility suggested by Brooks, that the rocks of lower Kichatna River are Mesozoic rather than Paleozoic; and if they are Mesozoic, it is possible that they may be correlated with the upper or Tordrillo formation, and that the older Mesozoic (Triassic?) rocks of the Broad Pass region may be equivalent to the slate formations of lower Kichatna River.

The formations that make up the mountains south of Broad Pass are separated from the Devonian limestone on the north by a broad valley floored with gravel deposits and showing the underlying bedrock in few places only. One such place is on Jack River, where shale, sandstone and conglomerate referred to the Tertiary are exposed. The slate, graywacke, and conglomerate beds of these mountains differ from the Devonian rocks lithologically, in the intensity of their folding, and in the degree of metamorphism that they exhibit. They show less alteration than the Devonian formations, and except in the somewhat greater proportion of conglomerate that they contain resemble closely the slate-graywacke series of Capps and the Tordrillo formation described by Brooks. Lithologically the "undifferentiated Paleozoic" rocks underlying the Tordrillo formation appear to resemble the rocks of the Broad Pass region tentatively assigned to the Triassic, for they show a greater development

[1] Eldridge, G. H., A reconnaissance in the Susitna basin and adjacent territory, Alaska, in 1898: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, p. 15, 1900.

of slate and less of the coarser sediments, such as graywacke and conglomerate.

Mesozoic rocks are widespread in Alaska south of the Alaska Range. Within the Susitna basin the Talkeetna Mountains are made up almost wholly of Mesozoic sediments intruded by igneous rocks, the only known exceptions being a small area of schist on Willow Creek, which Capps[1] assigns to the Paleozoic, and a somewhat similar area at the head of Matanuska River. Each year evidence accumulates to show that much of the Valdez and Orca groups, constituting a large part of the Chugach Mountains, are of Mesozoic and probably of Jurassic age. Triassic sediments are present in Chitina Valley, in the upper parts of Copper and Susitna River valleys along the south flanks of the Alaska Range, and in Kenai Peninsula. All the older associated formations whose ages have been determined are Carboniferous, yet some of the schists are believed to be older than Carboniferous. The Carboniferous and older rocks make up a comparatively small part of the whole complex of formations.

There is, then, a great area of Mesozoic sedimentary deposits south of the Alaska Range in south central Alaska, made up chiefly of slate, graywacke, conglomerate, and limestone, that as a whole are less metamorphosed than the older formations. The formations south of Broad Pass are of the same lithologic nature, and although there is no conclusive evidence at hand by which they can be definitely correlated with other formations of the region, the probabilities seem to be that they are more recent than Paleozoic, and that if they are the equivalent of either the Tordrillo or the underlying formations the correlation with the Tordrillo is more likely. This is the most important reason for assigning them to a particular part of the Mesozoic.

A great thickness of Mesozoic beds of similar character and in large part of Jurassic age is exposed in the Nutzotin Mountains, which form the eastern part of the Alaska Range.[2] Slate, graywacke, and conglomerate constitute the Jurassic part of this group, so far as is known. Triassic limestone and slate were seen at only a few localities, but probably are more widely distributed than the evidence at hand shows. The close lithologic resemblance and the evidence of fossils, so far as it goes, suggests the correlation of the formations of the Nutzotin Mountains with those of the Valdez Creek and Broad Pass regions.

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[1] Capps, S. R., The Willow Creek district, Alaska: U. S. Geol. Survey Bull. 607, p. 23, 1915.

[2] Moffit, F. H., and Knopf, Adolph, Mineral resources of the Nabesna-White River district, Alaska: U. S. Geol. Survey Bull. 417, p. 27, 1910.

UNDIFFERENTIATED MESOZOIC (?) ROCKS.

CHARACTER AND DISTRIBUTION.

The mountains south of the east fork of Wells Creek and about the lower half of the glacier in which West Fork of Susitna River rises are composed in large part of sedimentary rocks, chiefly slate and limestone. These rocks form a complex of beds that could not be differentiated in the time available and that differ considerably in aspect and in proportionate amount of different rock types from any of the formations already described, the difference being principally a much greater proportion of limestone, thin bedded and locally highly metamorphosed, interstratified with the slate. They lie in the strike of the Jurassic (?) sedimentary formations of Jack River, but because of their different lithologic character and their somewhat different structure it seems best to consider them separately, especially since it is thought possible, if not probable, that they may include Mesozoic rocks older or younger than Jurassic. These formations differ not only from other sedimentary formations of the region but also among themselves.

The northern half of the mountain mass between upper Nenana River and the east fork of Wells Creek is made up chiefly of alternating limestone and argillite beds, having gentle dip and showing distinct bedding. These sedimentary deposits were intruded by igneous rocks, but seemingly have not been greatly disturbed by them. Near the head of Wells Creek, where these sediments were examined with more care than at any other place, they comprise thin-bedded light-blue or light-gray white-weathering limestone, in part silicified and otherwise altered, interstratified with thin beds of dense, siliceous dark-blue argillite, much jointed and presenting a more or less iron-stained exterior. The contrasting colors of the rocks give their large exposures a variegated appearance, and in connection with the irregularities of erosion surfaces produce a complicated marking on bare mountain sides that immediately catches the eye. (See Pl. VIII, *A*, p. 22.) The limestone is cut by numerous seams of calcite, some of which is coarsely crystalline. A little pyrite is scattered through the argillite. Dikes and lens-shaped sills of rhyolite porphyry and medium to fine grained diorite are associated with the limestone and argillite. The bedding strikes about N. 80° E. and dips southeastward at angles ranging from 20° to 40°. It is estimated that the thickness of the exposed beds is at least 1,500 feet. These beds are probably part of a gentle fold, but are cut off from other terranes by igneous rocks and gravel deposits, so that they are not known to be a part of any neighboring formation on the north or on the south. Moreover, their open folding is discordant with the close folding of the other sedimentary formations near by.

A series of variegated, gently dipping sedimentary beds, composed chiefly of white silicified limestone, interstratified with thin beds of dark impure limestone and of dark-colored argillite, is exposed between the glacier of the two western branches of Susitna River. This series contains a greater amount of limestone, some of it in thick massive beds, than that south of Wells Creek, and the correlation of the two may be made only with a certain degree of reservation. These rocks are separated from the rocks on the south or southwest, to be described next, by a great fault.

The mountains between Nenana River and the glacier at the head of West Fork of Susitna River consist chiefly of closely folded slate, schist, and altered limestone. The limestone is thinly bedded, bluish-gray, and is locally silicified. Where it was impure pressure and chemical alteration brought about the formation of new minerals, such as mica, and gave the rock the appearance of schist. Black carbonaceous shale or slate and gray sericitic schist, composed of mashed graywacke, are associated with the limestone, and in fact make up most of these mountains. These beds have about the same strike as those south of Wells Creek, but, as already stated, are more closely folded and are more altered. Except for their greater proportion of limestone, they resemble part of the slate and graywacke series of Jack River.

AGE AND CORRELATION.

The age of these sediments is unknown. It is perhaps possible but does not appear probable that they correspond in part with some of the Devonian formations. On the other hand, it seems much more likely that they are of Mesozoic age, and are to be correlated either with the Triassic slates and limestones of the Valdez Creek district or with the Jurassic (?) sediments of Jack River. They may even include beds belonging to both of these groups.

Cenozoic Rocks.

TERTIARY SEDIMENTS.

CANTWELL FORMATION.

CHARACTER AND DISTRIBUTION.

The Tertiary sedimentary deposits of the Broad Pass region include the Cantwell formation and a small area of beds that somewhat resemble the rocks of the Cantwell formation but are not identical with them. The Cantwell formation consists of conglomerate beds, slate, shale, sandstone, quartzite, grit, graywacke, and highly metamorphosed equivalents of all these rocks.

In the vicinity of Nenana River, near the mouth of Jack River, the Cantwell formation shows open folding (see Pl. III, *B*, p. 8), but

this folding becomes closer toward the east and is accompanied by a progressive increase in the degree of metamorphism, so that the little-altered rocks in the western part of the mapped area are represented in the mountains between the heads of Nenana River and Yanert Fork by mashed conglomerate and schist. The thickness of beds included in the formation can not be less than 2,700 feet and may be much more. These beds probably rest unconformably on the Devonian schist and limestone that limit them on the south.

The name Cantwell was proposed by Eldridge to designate a "series of conglomerates and coarse sandstones which was encountered in the banks of the Cantwell [Nenana] River, about 10 or 15 miles above the forks."[1] This name was adopted by Brooks, who studied the formation on the north side of the Alaska Range and traced it eastward from Muldrow Glacier to Yanert Fork.[2] It is applied here to the eastward extension of the beds included in the formation by Eldridge and Brooks.

The changing character of the Cantwell formation can be best shown by describing the beds observed at different localities between the mouth of Jack River and West Fork of Susitna River. A comparison of these localities brings out a number of features, some of which have just been mentioned and the most prominent of which are a progressive increase in closeness of folding and in degree of metamorphism and a decrease in the amount of conglomerate, with a corresponding increase in the relative amount of fine-grained sediments, from west to east. These descriptions apply to the southern border of the formation, for the character of the beds in the central and northern parts of the area occupied by the Cantwell is unknown except where it was studied by Brooks.

Just below the mouth of Jack River the Nenana in its northward course enters a narrow valley between black, rugged mountains whose upper parts are made up chiefly of massive conglomerate beds (Pl. VII, *B*, p. 18) that dip gently northward and rest on a narrow belt of granite which separates the conglomerate from the Devonian limestone and schist on the south. Inconspicuous beds of finer-grained rock (shale and grit), which in many places are hidden by a talus of conglomerate blocks, are interbedded with the conglomerate. These beds, when viewed from the vicinity of the mouth of Jack River, are seen to maintain their low northerly dip for several miles down the Nenana. The conglomerate is composed of well-rounded gravel and cobbles of quartz, quartzite, slate, and an acidic igneous rock set in a siliceous cement. Cobbles as much as 7 inches

[1] Eldridge, G. H., A reconnaissance in the Sushitna basin and adjacent territory, Alaska, in 1898: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, p. 16, 1900.

[2] Brooks, A. H., The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, p. 78, 1911.

in diameter were observed. Intercalated with the conglomerate are thinner beds of sandstone, quartzite, and dark-blue carbonaceous argillite. A contact of the Cantwell formation and the underlying granite showed the two rocks to be united as if fused together. The lowest part of the sedimentary formation in view at this contact exposes 4 feet of slightly mashed conglomerate, with closely spaced joints parallel to the contact, resting on the granite. This is overlain by 6 feet of closely jointed quartzite, which in turn is followed by massive conglomerate.

A small area of fine-grained dark-colored carbonaceous sediments, 3 miles east of the mouth of Jack River, lies in contact with limestone on the south and is separated from the conglomerate and associated beds on the north by a narrow tongue of granite that runs out from the large intrusive mass to the east. The rocks of this area are massive for the most part, but present schistose phases. The most abundant type of rock is dark-blue argillite, flecked with grayish scalelike spots. It is shown by the microscope to consist mainly of small quartz fragments associated with scattered feldspar grains and considerable black carbonaceous matter, in which are fairly abundant sericite shreds. Another phase of the argillite is schistose and merges into graywacke. The argillaceous beds of the area so closely resemble the argillaceous beds intercalated with the conglomerates of the near-by Cantwell formation as to warrant a correlation of the two and to justify the belief that they were separated by the intrusion of the granite. Yet this detached area of Cantwell rocks (if such it is) shows by the steep dips and variable strike of the beds a considerable structural discordance with the gently dipping beds of the main area. This locality is the only one where the Cantwell formation was seen in contact with the older sediments, yet the beds had been so much disturbed by pressure and movements as to make the interpretation of their relations uncertain.

Wells Creek has two main branches. The western branch is formed by three streams that head in an area of Cantwell sediments that forms the mountains of the divide between upper Nenana River and Yanert Fork. This area is separated from that to the west by an intruded mass of granite about 7 miles across from east to west. Its southern border was examined with some care at several places.

About a mile east of the western border of the area a section of the beds from the valley to the mountain top was studied. From the base of the mountain, at an elevation of 3,600 feet, to an elevation of 5,600 feet the beds consist predominantly of massive dark-gray, somewhat schistose graywacke, composed of subangular to rounded pieces of quartz and black slate, set in siliceous cement. Intercalated with the graywacke are beds of black carbonaceous shale or

slate containing abundant leaf impressions, and siliceous conglomerate, locally somewhat schistose. Thin lenses of the conglomerate were seen in the graywacke, some of which, especially those in the more quartzose graywacke, contain angular and rounded slate fragments.

The mountain above an elevation of 5,600 feet is made up of thickly bedded conglomerate, mashed and in places so schistose that the original texture is nearly obliterated. Most of the conglomerate, however, retains a semblance of its original structure, the coarser components appearing as elongated lenses which the finer, partly micaceous constituents enwrap. The conglomerate at this locality is light greenish or yellowish and dips northward at angles ranging from 35° to 60°, which indicates somewhat closer folding than that on the Nenana below Jack River.

The next locality examined is near the westernmost branch of the west fork of Wells Creek. The following detailed section represents part of the Cantwell formation exposed in this locality:

Section of a part of the Cantwell formation as exposed on the western branch of Wells Creek.

	Feet.
Black shale with plant impressions, alternating with beds of massive graywacke, in some places approximating a sandstone	1,200
Massive conglomerate, somewhat contorted, composed predominantly of white quartz pebbles, the largest three-fourths inch in diameter	200
Thin bed of shale	50
Unexposed	several hundred feet.
Schistose conglomerate	15
Silicified tuff	15
Alternating schistose conglomerate and schistose graywacke, including beds of shattered black slate and lenslike intercalations of quartzite	50
Dense, light-colored tuff, very hard	5
Rather schistose conglomerate, grading into schistose graywacke, which in turn grades into schistose conglomerate, the whole group containing lenticular beds of tuff	15
Graywacke, with lenses of quartzite and shattered carbonaceous slate	30
Siliceous conglomerate, rather massive	2
Graywacke	3
Carbonaceous slate, much shattered and slickensided	8
Graywacke, slightly schistose	15
Crushed slate and schistose graywacke	5
Graywacke, fairly massive	5
Covered, probably mostly graywacke	20
Schistose and altered graywacke, injected with quartz stringers and lenses	10
Granite, exposed	30
Gravel deposits of the valley floor.	

The silicified tuff of this section loks like quartzite, but when examined under the miscroscope was found to be composed of small pieces of quartz, some orthoclase, and a little plagioclase, all distinctly fragmental, set in a dense microcrystalline ground.

A traverse was made up the west branch of the west fork of Wells Creek to the divide that separates the stream from Yanert Fork. For a distance of 2¼ miles south of the divide the rocks consist of alternating beds of mashed conglomerate and dark-blue to black slate, derived from the carbonaceous shale. Some phases of the slate have a crinkly surface and satiny luster. Many of the beds might properly be called schists. At one locality, 2 miles south of the divide, the carbonaceous plant-bearing shales contain seams of lignitic coal from 2 to 2½ inches thick. The formation as a whole has a black aspect, due in considerable degree to the large amount of carbonaceous matter contained in it. Southeast of the saddle at the head of this stream there are numerous dikes of rhyolite porphyry, which show well-formed phenocrysts of quartz and feldspar in a greenish ground. The stream gravels contain, in addition to the types of rock described, bowlders of fine-grained diorite porphyry, conglomerate of a different appearance from any seen in place, composed of oval cobbles of granite and other igneous rocks, and a plicated phase of the near-by mashed conglomerate.

Another traverse was made up the middle branch of the west fork of Wells Creek. Near the southern boundary of the Cantwell formation the stream has cut closely folded beds of slate, graywacke, and conglomerate, all considerably mashed, the conglomerate being altered almost beyond recognition. The slate is crushed and shows slickensided surfaces. In the schistose conglomerate are small, thickly lenticular masses composed largely of tiny pyrite cubes. The formation for 2 miles north of this place consists of slate, graywacke, and conglomerate. All these rocks have undergone regional metamorphism, but the graywacke and conglomerate have suffered most. Much of the slate, however, has a crinkly surface, a feature that is thought to have developed later than the cleavage and that shows something of the compression to which the beds have been subjected. Folding of the beds is also pronounced, and the dips are steep, ranging from 80° N. to 80° S. Numerous quartz veins, seemingly unmineralized, the largest a foot in thickness, were injected into the sediments. These rocks continue northward to the head of the stream and into the basin of Yanert Fork. As a whole, they are dark grayish to black in color and give the mountains which they form a dark somber aspect and rugged contours.

At the head of Nenana River another intruded mass of granite interrupts the continuity of the Cantwell formation for a distance of about 8 miles from east to west. The rocks east of this granite

area and north of the glacier at the head of West Fork of Susitna River were not examined except from a distance, yet from their appearance and the morainal material brought down on the west side of the glacier it is believed that the Cantwell forms the mountains around the west side of the base of Cathedral Mountain. The beds consist of dark slates and mica schist, the schist representing the coarser grained, more altered members of the formation. The most common form of the schist is dark reddish to bluish gray and shows an iron-stained surface, the result of weathering. The cleavage planes glisten with mica scales, and the cross fractures show numerous thin quartzose lenses which represent the original pebbles in the rock from which the schist was derived. It is only after having traced the Cantwell formation through its progressive stages of alteration that an observer recognizes the schist of this locality as the mashed equivalent of the massive conglomerate so prominent in the mountains near the mouth of Jack River.

A comparison of the Cantwell formation, as it is exposed between Nenana River and the glacier of the West Fork of the Susitna with that part of it on the north side of the Alaska Range west of Nenana River, where it was examined by Brooks, shows some further characteristics of this group of sediments. According to Brooks:[1]

> The Cantwell formation includes a series of heavy conglomerates interbedded with a few shale layers and succeeded by finer conglomerates and red sandstones interbedded with gray and black clay shales.

Brooks says further that the name was applied by Eldridge to the coarser, basal part of the formation, and that when traced to the north and west the conglomerates and coarse sandstone are succeeded by reddish sandstone and gray, drab, and black shales. Some of the sandstones are bright red, but the color varies to brown or reddish brown. Both argillaceous and arenaceous shales are present, the arenaceous shales grading into shaly sandstone. Some of the shale beds contain a large amount of carbonaceous matter and include small coal seams. Brooks writes:[2]

> A typical section near the camp of August 9, on the West Fork of the Toklat, showed a basal conglomerate about 20 feet in thickness resting unconformably on the upturned edges of Paleozoic slates and limestones. This bed contains pebbles of the underlying rocks. Above it is exposed about 20 feet of carbonaceous shale, and this in turn is overlain by a heavy quartz and chert conglomerate containing sandstone lenses, which probably has a thickness of 100 to 200 feet and passes upward gradually into a grit and sandstone series with local conglomerate layers. This upper member is made up of heavy sandstone and grit, thin-bedded sandstone, and sandy shales which on weathering have an iron stain, together with considerable carbonaceous clay shale. The sandstone and shale member probably aggregates 1,200 feet in thickness at this

[1] Brooks, A. H., The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, p. 78, 1911.
[2] Idem, p. 79.

locality. One small area of these rocks, made up chiefly of conglomerate and red sandstone, was found on the Tonzona, where they formed a syncline resting on the cherts and slates of the Tonzona group. The most extensive exposure of them occurs in a belt of unknown width stretching from the McKinley Fork of the Kantishna to the Nenana Valley and probably beyond. In this area, especially toward the Nenana, lava flows interbedded with the conglomerate are very prevalent. In some localities these volcanic rocks form over half of the thickness of strata exposed belonging to this formation. These lavas appear to be chiefly andesites, but also include rhyolites and basalts. That they were surface flows is indicated both by their stratigraphic relations and by the amygdaloidal and columnar structure that some of them exhibit. Some tuffaceous beds also occur in this formation. The Cantwell formation is cut by diabase dikes and some granitic stocks.

This description shows still further the complexity of the Cantwell formation. The part of it east of Nenana River, between the mouth of Jack River and Nenana Glacier, probably corresponds in large measure to that part of the formation which Eldridge described under the name Cantwell, but it should be borne in mind that this is not necessarily the base of the Cantwell, for the granite that forms the base of the mountains in this area was intruded into the sedimentary beds and may not everywhere have followed the contact of the basal beds and the underlying rocks. No such amount of volcanic material was seen along the southern border of the area as was found west of Nenana River by Brooks.

According to Brooks, the structure of the Cantwell formation west of Nenana River is characterized by broad, open folds, accompanied by faulting. Such folding is seen along the Nenana below Jack River, where the inclination of the massive conglomerate beds indicates a broad, open syncline pitching gently eastward.

A narrow belt of granite separates the lowest Cantwell beds from the adjacent Devonian limestone in this vicinity, and it is not evident whether the contact relation of the two is that of faulting or of depositional unconformity. The scarplike southern face of the mountains and the straight front of the ridge strongly suggest a great fault, yet no conclusive evidence of faulting was observed. The unconformable relation of the Cantwell and underlying Paleozoic formations farther west, however, is well established.

East of Nenana River, as has been pointed out, the folding becomes more and more intense and the original character of the beds is much altered. At the head of Wells Creek the structure is much more complicated than on the Nenana. The beds dip steeply, some to the north, some to the south; the folds are compressed and complicated but not isoclinal, their axial planes dipping south or north in neighboring localities. A small fold on a branch of Wells Creek indicates the kind of folding that characterizes the formation in this vicinity. (See fig. 3.)

The width of the area occupied by the Cantwell formation also increases from east to west, but probably reaches a maximum somewhere between Nenana River and Wells Creek and decreases to the east. Near Muldrow Glacier the width of the area is about 2 miles, at Nenana River it is at least 20 miles, and at the lower end of Yanert Fork Glacier it is probably 17 miles, for Capps found coarse sediments at the head of Wood River that are thought to belong in the Cantwell formation.

Brooks found abundant evidence to show that, toward the west at least, the Cantwell rests unconformably on Paleozoic formations. No conclusive evidence of unconformity was seen east of Nenana River, for in most places the lowest exposed beds of the Cantwell are in contact with granite which is intruded into the formation. The one locality where rocks believed to be Cantwell are in contact with the older limestone is of such a character, owing to disturbing movements, that there is uncertainty as to the true relation of the two formations.

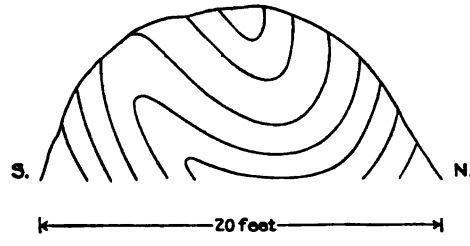

FIGURE 3.—Sketch of a small fold in beds of the Cantwell formation on a tributary of Wells Creek.

The thickness of the Cantwell formation can not be stated with accuracy. Much of the original deposit has been removed by erosion, and furthermore the survey of 1913 was not sufficiently detailed to furnish data for more than approximate measurements. Brooks found that the Cantwell at the head of Toklat River had a thickness of at least 2,000 feet, and noted that the thickness increased toward the east.

Near the mouth of Jack River the contact of the conglomerate and granite was observed at an elevation of about 3,100 feet above the sea. The mountain top is 5,860 feet above the sea. After making the necessary correction for the dip of the beds, it is found that this part of the Cantwell is approximately 2,700 feet thick; but it must be remembered that this measurement takes no account of a great thickness of overlying finer grained beds exposed farther north.

The Cantwell formation is intruded by great masses of granite and related granular rocks and is cut by light-colored porphyritic dikes. These intrusions must have had some disturbing influence on the rocks intruded, but so far as has been observed they have not produced conspicuous contact effects. The intrusive rocks are described on pages 57, 59, and 64.

The character of the sediments composing the Cantwell formation indicates continental deposition. This conclusion is suggested by

the great thickness of conglomerate and the presence of intercalated beds of fine-grained, leaf-bearing material and of thin lignitic coal seams. Apparently the gravels were derived from an elevated land mass near by and were spread over a lowland occupied in part by marshy areas and bodies of quiet water. The accumulation of great thicknesses of conglomerate and graywacke made up of little-altered constituents is commonly regarded as indicating rapid degradation and deposition, such as might be expected in a region of cool and humid climate; but the fossil plants in the leaf-bearing deposits and coal seams of the Cantwell formation are those of a temperate or warm climate. Too little is known of the Cantwell formation to warrant a definite statement as to the location of the source of the material composing it, yet an examination of pebbles from the conglomerate beds along the southern border of the area and a comparison with older formations north and south of the range yields some evidence for assuming that the land mass lay in the south. Evidence of probably greater weight is found in the coarseness of the material constituting the southern border of the formation, but none of the evidence can be conclusive till a more detailed study of the whole area is made. Another account of the Cantwell formation has been given by Mr. Pogue.[1]

AGE AND CORRELATION.

The Cantwell formation is of early Tertiary (Eocene) age. This determination is based on the evidence of fossil plants collected in several places on the west fork of Wells Creek. The plant remains are contained in beds of shale or slate and sandstone interstratified with beds of conglomerate. Several collections were made, and the following forms were identified by F. H. Knowlton and Arthur Hollick:

Locality No. 6565. Ten miles east of mouth of Jack River.

Taxodium tinajorum Heer.	Populus arctica Heer?
Taxodium dubium (Sternberg) Heer?	Daphnogene kanii Heer.
Sequoia langsdorfii (Brongniart) Heer?	

Locality No. 6567. Ten miles east of mouth of Jack River (near 6565).

Aspidium heerii Ettingshousen?	Ginkgo adiantoides (Unger) Heer?
Taxodium dubium (Sternberg) Heer?	

Forms like three of the species in lot No. 6565 were collected by Brooks from a locality within the Cantwell formation in one of the upper tributaries of Toklat River.[2] The weight of other evidence,

[1] Pogue, J. E., The Cantwell formation, a continental deposit of Tertiary age in the Alaska Range: Jour. Geology, vol. 23, pp. 118–128, 1915.

[2] Brooks, A. H., op. cit., p. 82.

however, led Brooks to believe that the Cantwell must be older than Tertiary and that the beds in which his plants were found had been faulted into the Cantwell. The possibility of such conditions, either in faulting or in folding, is recognized for the Wells Creek localities, but is believed to be highly improbable. The Cantwell formation, then, is to be correlated with the widespread Eocene Tertiary sediments in Alaska that have been included under the name Kenai formation, although what has been called Kenai in some places is a complex that includes beds of Cretaceous age.

TERTIARY ROCKS ON JACK RIVER.

Jack River, after emerging from the mountains south of Broad Pass, flows for a mile or more through a canyon that gradually becomes wider and shallower till it finally disappears near the middle of the old Nenana-Chulitna Valley. The walls of this canyon consist of shale, graywacke, conglomerate, and sandstone. These rocks are altogether different from the Jurassic (?) formation on the south and are not identical with the members of the Cantwell formation to the north, although they have many features in common. They were seen only in the canyon and in the gulches tributary to it, so that the area known to be occupied by them is small. On the south side of the area these rocks consist of black shale containing a few thin graywacke beds, all dipping steeply northwest. The shale is followed on the north by massive conglomerate of grayish color which strikes northeast and dips 50°–60° SE. The contact of the shale and conglomerate was not seen. The conglomerate near the shale contains bowlders, the largest a foot in diameter, but is followed on the north by finer conglomerate that contains well-rounded pebbles of quartz and black flint, not more than half an inch in diameter. This finer conglomerate rests on yellowish-gray sandstone and shale beds that dip 30°–40° SE. These observations would indicate for the yellowish conglomerate and shale a thickness of not less than 2,000 feet, yet the exposures are such that this estimate can not be considered as wholly reliable. The shale and sandstone are soft, and the conglomerate, although well consolidated, weathers readily to gravel and sand.

No fossils were found in these rocks, but they are believed to be much younger than the slate, graywacke, and conglomerate of the mountains on the south and the near-by Devonian limestone and schist on the north. They probably represent some part of the Tertiary deposits, but their yellow color and slight metamorphism distinguish them from any part of the Cantwell formation examined by the writer.

QUATERNARY DEPOSITS.

By JOSEPH E. POGUE.

Much of the Broad Pass region is mantled by a covering of Quaternary alluvium, which consists of unconsolidated materials laid down by water and ice during the glacial epoch and those since deposited by the streams.

GLACIAL DEPOSITS.

The glacial deposits are primarily the result of a period of intense glaciation, characterized by transgression and coalescence of mountain glaciers into an ice sheet that covered all but the highest portions of the region. The extent of this ice mantle is now marked by silts, sands, gravels, and bowlders dropped during its retreat, laid down by streams escaping from its margin, and deposited in lakes left in its train. The structure and form of these deposits are fully discussed in the section on glaciation (pp. 66–73).

The distribution of the glacial deposits, as shown on the geologic map, conforms to the topography of the region, as relief was a controlling factor in their disposition. Their thickness is greatest in the broad valleys, whence they thin out on the gentler gradients and end against the steeper slopes in an irregular boundary, roughly concordant with the elevation contours. The maximum thickness of these sediments is nowhere disclosed in measurable section, but their topographic configuration indicates that their greatest vertical development is to be rated in hundreds of feet. Their thickness, however, is an exceedingly variable quantity, and in a broad way they must be regarded as a comparatively thin blanket or veneer, thinning out here and thickening there, with only general accordance to the underlying hard rock floor.

The surface configuration of the glacial deposits, except where channeled by present watercourses, has not been materially affected by postglacial erosion. About the borders of the gravel sheet, however, where slopes rise rather abruptly from its thin edge, special opportunity has been afforded for erosion, and such boundaries have not only been notched and serrated but have also suffered some downward migration, leaving a stripped belt of variable though unknown width in their wake.

RECENT DEPOSITS.

The recent deposits include alluvial material along present watercourses, rock débris of existing mountain glaciers, lake sediments, and colluvial deposits (those due to gravity) at the base of steep slopes. The first two classes of deposits only have sufficient areal development to appear on the geologic map.

The streams of the Broad Pass region comprise two groups—those heading in glaciers and laden with ice-ground rock flour, and clear-water streams, carrying no sediment except in time of rain. The first group, as represented by Susitna, Nenana, and Yanert Fork rivers and some of their tributaries, are torrential in summer and transport vast amounts of sediment. In their upper courses especially they are overloaded and divided into numerous braided and anastomosing channels spread over broad flood plains. These channels are constantly shifting, and material deposited in one season may be worked over and respread the next. Many of the clear-water streams are turbulent and narrow in their upper stretches, but where they emerge on the gravel floor of the broader valleys their velocity is checked and they develop flood plains on which sediments brought down in time of flood are deposited. These streams, however, nowhere form the intricate network of channels so characteristic of glacial rivers nor are their flood-plain deposits in all places sufficiently extensive to show on a small-scale geologic map. All clear-water streams eventually drain into the silt-laden glacial rivers, which carry much of their own burden beyond the confines of the region.

In character the flood-plain deposits consist of silts, sands, and gravels, showing distinct stratification and sorting. The gravels increase in abundance and in size of components toward the source, and especially near the glaciers the flood plain is covered with a cobble pavement, composed of rocks of the different types found in the drainage basin. Many of these pavements show a conspicuous accordance in size of individuals, and their development depends not only on depositation by swift and shifting currents, but also on subsequent removal of finer material by water of decreased velocity incompetent to roll the larger individuals.

The recent glacial deposits represent the rock débris brought down by the active glaciers and spread over their frontal lobes. This material, along with rock flour, is supplied to the streams that emerge from the ice masses, and is subsequently distributed over the broad flood plains that lie before the glacier fronts. These deposits and also the erosional activity of ice are treated more fully in the section on glaciation. (See pp. 66–73.)

Lakes are conspicuous features throughout the lowland areas of the region. (See Pl. III, *A*, p. 8.) Most of them are clear and limpid, but some form settlement basins for turbid glacial streams and in time of heavy rains all receive increments of mud. Many of these lakes have no outlets and ultimately disappear from the combined action of slow sedimentation and lateral encroachment of vegetation. In the aggregate lake deposits are not important in the region and are nowhere conspicuous, for a basin once silted up is obscured by a

covering of vegetation and would not be observed until subsequently dissected by erosion.

A final type of deposit, of great local importance but of little areal extent, is one that depends on the pull of gravity exerted on rock fragments abundantly supplied through the agency of ice, frost, and the water that flows during thaws. These deposits include talus fans, rock slides, rock glaciers, and soil flows. The essential distinction of these is that they are not deposited in water. In a subpolar region like this one, where the temperature most of the year ranges below the freezing point of water, the surface rocks, especially where unprotected by a covering of vegetation, are rapidly disintegrated by the prying action of freezing water. This process, which is most active in spring and fall, results in the abundant development of rock fragments of different sizes, depending on the nature and structure of the rock. These fragments, according to their size and to the gradient and configuration of the slope, tend to migrate downward and give rise to deposits of diverse form. Where the slopes are vertical or precipitous the rock fragments, as they become detached, fall or slide rapidly downward until they become arrested on a flatter slope, where they accumulate in fringing aprons or coalescing fans, whose surface is inclined at the steepest angle at which the materials composing the mass will lie. In many places instead of being supplied uniformly from the top of such slopes, the fragments are concentrated by surface inequalities and develop symmetrical fans resembling in shape inverted half cones. Talus deposits of the kinds enumerated are especially conspicuous in those mountains that have been dissected by recent glaciation and now expose the steep slopes of their ice-carved amphitheaters or cirques, unprotected by ice, to the ravages of freezing and thawing. It is the finer material from such accumulations that is chiefly supplied in time of flood to the clear-water (nonglacial) streams and that is subsequently laid down on their flood plains.

Where the slopes are less precipitous they commonly show depressions in which the rock waste accumulates in longitudinal rock trains or slides, composed of a loose assemblage of angular pieces, ranging in size, according to the character of the rock, from small fragments to great blocks several tons in weight. The summits of many of the mountains can only be reached by climbing over such masses of incoherent rocks, for firmer paths of ascent are blocked by sheer cliffs. These bodies of rock, especially if made up of coarse components, have gentle slopes near their bottoms and increase in gradient toward their point of supply. In the course of their development their upper portions periodically reach a state of unstable equilibrium and adjustments take place, accompanied by a settling

of the mass or by slides and avalanches. Such phenomena are less marked in bodies of finer material (such as those formed of slate fragments), since adjustments in these are frequent and gentle and their structure does not usually permit an overloading of the upper portions. Movement within these bodies is greatly facilitated by freezing and thawing, as well as by the presence of interstitial ice, and their progression, at least in their lower portions, is analogous to that of an extremely viscous material.

Generally these rock trains have little extent and are local features; they are everywhere abundant on the upper slopes of the mountains and are not uncommon at lower elevations. At favored localities, where several trains coalesce or the catchment area is especially large, the rock mass may take on a glacier-like form and extend a short distance down the valley. A few examples of this kind were observed, and they bear a partial analogy to the striking rock glaciers so typically developed in the Nizina district, as described by Capps,[1] though they are nowhere so extensive nor do they so completely simulate the character of an ice glacier. The rock glaciers described by Capps range to a maximum of 2½ miles in length. In the Valdez Creek region a rock glacier over a mile long was observed.[2] The longest rock glacier noted in the Broad Pass region scarcely exceeded one fourth of a mile in length.

On gentle slopes and the rounded tops of the lower mountains rock fragments tend to accumulate in thin sheets, which to some degree protect the underlying surfaces from disintegration. If the slopes be plane, the débris does not concentrate into trains or "streams," but slowly migrates downward as a uniform covering. That movement takes place is only inferential for the coarser material, but finer detritus in many places shows a marked streakiness of surface, owing to the arrangement of particles as a result of creep. The best example of this kind was noted near the top of the southern slope of a buttelike mountain west of Wickersham Creek. The underlying rock is slate, and the slope is covered with a thin veneer of slate fragments and soil, presenting a furrowed appearance, owing to alternate vertical strips a few inches wide of rock fragments and soil, the soil standing a bit higher than the rock.

Soil flow or creep is not confined, however, to the upper slopes, which are bare of vegetation, but takes place also on lower declivities covered with moss and grass, where it produces a surface configuration of peculiar character. Such slopes show a succession of roughly lobate areas, each thinning out upward and partly overlapped by another like shingles. These areas are caused by the gradual move-

[1] Capps, S. R., Rock glaciers in Alaska: Jour. Geology, vol. 18, 1910, pp. 359–375. See also Moffit, F. H., and Capps, S. R., U. S. Geol. Survey Bull. 448, pp. 52–59, 1911.

[2] Moffit, F. H., U. S. Geol. Survey Bull. 498, p. 41, 1910.

ment of the soil, under the influence of gravity, aided by the high moisture content and the action of freezing and thawing and restrained by the interlocking mesh of roots and fibers. They probably do not represent in themselves the total movement, but are rather the surface expression of steady creep, and the process may be compared to the flow of a viscous substance, such as pitch or asphalt, on an inclined plane. No examples at all comparable in fineness of development to the "soil flows" at the head of Valdez Creek[1] were seen in this area, though such phenomena are abundant in the mountains east and west of upper Butte Creek.

IGNEOUS ROCKS.

By Joseph E. Pogue.

SUMMARY.

Igneous rocks occupy large areas and have conspicuous topographic expression in the Broad Pass region. The geologic map (Pl. II, in pocket) shows that they fall into two main classes—granular intrusives that invaded the sedimentary formations and lava flows poured out on the surface. The granular intrusives include bodies of granite, granite porphyry, quartz monzonite, quartz diorite, olivine gabbro, and gneiss (probably an older intrusion altered by pressure). The lava flows include a series of acidic effusive rocks, principally rhyolites, trachytes, and andesites, which are closely associated with one of the large granitic intrusions, and a series of basic rocks, basaltic and andesitic, with interbedded tuffs, which show no connection with intrusive bodies. The sedimentary formations, moreover, are cut throughout by acidic dikes, whose increase in abundance toward borders of igneous masses suggest a genetic relation.

The igneous formations and their ages, so far as determinable, are summarized in the following table:

Igneous rocks of the Broad Pass region.

Post-Eocene	Amygdaloidal andesite.
Tertiary (in part)	Intrusions of granite, quartz monzonite, and quartz diorite, accompanied or followed by injection of granite porphyry and by extrusion of acid lavas.
Post-Jurassic (?)	Intrusion of olivine gabbro.
Pre-Tertiary	Gneiss (altered granular intrusive).
Triassic (?)	Basic lava flows with tuff beds.

[1] See U. S. Geol. Survey Bull. 498, pls. 5, *B*, and 6, *B*, 1912.

The Triassic basic lavas, because of their bedded character, the associated deposits of tuff, and their general structural analogy to the sedimentary formations, have been described with the sedimentary beds. (See pp. 26–28.)

GNEISS.

Southwestward from Butte Lake to the valley bordering Deadman Mountain there extends a belt of gneissic rock which forms rounded mountains of moderate elevation. This area is nearly surrounded by glacial gravels; on the south only it adjoins an intrusive mass of quartz diorite. Near the head of the east fork of Deadman Creek there are a few outcrops of a similar rock, evidently representing a prolongation of the belt beneath the gravels of the intervening valley.

The rock is a typical biotite gneiss, differing from place to place in coarseness, in the quantity of biotite it contains, and in degree of foliation. The average type is dark brown and closely foliated, carries considerable granulated quartz, and glistens with abundant mica. A specimen collected near Butte Lake, when examined under the microscope, was seen to be composed of a mosiac of quartz fragments, carrying orthoclase, plagioclase, and brown biotite associated with magnetite. Its characteristics are those of an igneous rock of granitic to monzonitic nature.

The dominant strike of the gneiss is about N. 50° E., and the dip is comparatively steep to the northwest. The area is intruded by dikes of andesitic porphyry and of a white alaskitic rock, which are probably related to the adjoining diorite intrusive. The metamorphism of the rock and its relation to the massive intrusive of probable Tertiary age (see p. 56) indicate a pre-Tertiary development for the gneiss. The gneiss accordingly is believed to represent a granitic intrusion of Mesozoic or Paleozoic time that became involved in subsequent metamorphism. In his study of the Mount McKinley region Brooks[1] refers to gneisses and gneissoid granites north of Tanana River which are older than the more extensive granite intrusions developed there.

GRANITIC INTRUSIVE ROCKS.

The sedimentary formations of the Broad Pass region are invaded by a number of granitic batholiths. Some of the rocks showing characters intermediate between granite and quartz monzonite correspond to granodiorite, but this term has not been used in this report. The intrusive rocks range from true granites through quartz monzonites to quartz diorites. In general, however, a single batho-

[1] Brooks, A. H., op. cit., p. 51.

lith does not exhibit this entire range in composition, but approximates the granite or the monzonite-diorite end of the series. It has been possible to apply these distinctions in the field, and the intrusives have been mapped, according to their dominant characteristics, as granite or quartz diorite, though each term, especially quartz diorite, must be understood as embracing monzonitic variations. Quartz diorite characterizes the eastern part of the region, where it is notably developed near Butte Creek and the glacier of the West Fork of the Susitna. The granite occurs in large areas west of the quartz diorite.

GRANITE.

Three large areas of granite have been mapped, one occupying the headwaters of Deadman Creek, Jack River, and Brushkana Creek; a second occupying a broad belt stretching northwestward from the region near the head of Nenana River and passing into the Alaska Range; and a third area adjoining the Nenana Glacier. The granite, broadly speaking, is a medium to coarse grained rock in which quartz in abundance, biotite, and feldspar can be readily recognized.

The large granite area that includes Deadman Mountain forms a series of rugged mountains bordered on the east by glacial gravels and ending on the north in an irregular contact against the Jurassic (?) slates of Jack River. This intrusive mass has not been traced southward and eastward to its limits. In its northern part the granite carries large areas of acidic lavas (see pp. 60–62) and of granite porphyry (see pp. 59, 60), which are probably later than the granite and represent a final expression of the magmatic intrusion. Throughout the formation there are scattered outcrops of rhyolite porphyry and of fine-grained diorite, regarded as dikelike intrusions injected at the close of or after the intrusion of the granite. It can not be affirmed whether the granite throughout the area under discussion represents a single batholith or several coalescing ones, though the rather constant character of the rock, so far as observations go, favors the first explanation. The average granite is a grayish medium-grained rock, showing about equal amounts of quartz and feldspar and carrying a subordinate sprinkling of biotite. A specimen from Deadman Mountain when examined under the microscope showed abundant quartz, a little biotite, and orthoclase predominating over acidic plagioclase.

The granite weathers rather readily to quartz feldspar sand, forming prominent talus fans of yellowish color which alternate with rock slides. This feature is especially prominent and characteristic toward the slate contact, east of upper Jack River, and suggests that the rock here has suffered hydrothermal alteration. The contact effects in this vicinity were studied in especial detail. The intruded slates and

limestones near the igneous border show silicification, baking, and pyritization (see pp. 25, 31, 33) and the granite itself near the sedimentary boundary shows close jointing and chemical alteration. North of the head of Seattle Creek the contact is bordered by a band a few feet in width of a white fine-grained phase of the granite, composed of quartz, feldspar, and a minute amount of muscovite. The feldspar is shown by the microscope to be about equally divided between orthoclase (including microline) and oligoclase, and the rock is regarded as an aplite of monzonitic character. The contact has no topographic expression.

The granite belt north of Nenana River cuts diagonally across the eastward-striking sedimentary formations developed there, forming part of a front range of mountains and passing into the Alaska Range proper. This area is not distinguished topographically from the adjoining sediments. The mass as a whole is composed of a gray, medium-grained biotite granite with coarser phases of considerable development characterized by bluish quartz and pink feldspar. Microscopic examination of both phases shows that plagioclase is subordinate to orthoclase and that the rock is a normal granite, rather than a quartz monzonite. The granite of this area appears to have had remarkably little contact effect on the invaded sediments, some recrystallization and silicification in the Devonian limestone and pyritization in the Cantwell formation being the only important consequences observed. Attention has already been directed (p. 42) to the supposed rending effect of the granite on an area of the Cantwell formation lying about 3 miles east of the mouth of Jack River. Contact variations in the granite itself were noted at several points. About 2 miles east of the mouth of Jack River is exposed a contact of the conglomerate and the granite, parallel to which for 50 feet the granite exhibits close jointing but no textural change. At a contact with limestone a few miles southeast of here, however, the granite in less than 2 miles passes from a very fine grained phase through a medium grained to a coarsely crystalline condition.

West of Nenana Glacier the Cantwell formation is interrupted by granite, which extends back into the Alaska Range toward the Yanert Fork Glacier. This intrusion forms a rugged range of glaciated mountains that show prominent vertical jointing (Pl. VIII, *B*, p. 22) and that carry perpetual snow on their summits. The contact with the Cantwell is not topographically indicated, though easily recognized from the difference in the nature of the two formations. The rock, so far as examined, proved to be a normal medium-grained biotite granite. Between the Nenana Glacier and the glacier of the West Fork of the Susitna is a further extension of the granite, presumably a continuation of the same intrusion,

although here the rock presents a gneissoid aspect. Under the microscope, however, it is seen to be composed of abundant quartz with orthoclase, a little microcline and acidic plagioclase, shreds and foils of biotite, and a few small crystals of green hornblende.

QUARTZ DIORITE.

Six areas of dioritic and monzonitic rock have been mapped, including one on either side of upper Butte Creek, an intrusion west of lower Butte Creek, a large body forming the southern portion of the sedimentary mountains bordering the glacier of the West Fork of the Susitna, an intrusion adjacent to Valdez Creek, and a body near Moose Creek. The absence of diorite from the western portion of the Broad Pass region is again emphasized. The diorite is readily distinguishable from the granite in that it shows in the hand specimen little quartz, considerable hornblende, scanty biotite or none at all, and scattered laths of feldspar in a feldspathic ground.

The quartz diorite area between upper Wickersham Creek and Butte Lake exhibits considerable variation within itself. The rock is typically a quartz-hornblende diorite, but its color ranges from dark to light, depending on the proportion of hornblende to feldspar. In the mountains immediately south of Butte Lake the rock carries titanite in conspicuous amount. This component is also prominent in the intrusives of the Coast Range of southeast Alaska.[1] Under the microscope the hornblende is seen to be a green, intensely pleochroic, iron-bearing variety. The plagioclase is mostly oligoclase and predominates over orthoclase. Quartz is fairly abundant and titanite is thickly distributed. Outcrops of a gray fine-grained phase, with components almost indistinguishable to the unaided eye, were noted near Wickersham Creek. This body invades the Triassic (?) slates, which near the contact are somewhat hardened and pyritized and carry foliated injections of the diorite magma.

The belt of gneiss that extends southwestward from Butte Lake is bordered by a body of quartz-hornblende-biotite diorite. A specimen collected from a tributary of Butte Creek is faintly gneissoid, though most of the occurrence is quite massive.

The intrusion west of lower Butte Creek invades the Triassic (?) slate formation, forming rounded mountains of moderate though conspicuous elevation among the gentler slopes of the sediments. The mass consists of medium-grained quartz-biotite-hornblende monzonite, fairly constant in character throughout, though locally presenting fine-grained dioritic phases. Microscopic examination of a typical specimen shows it to be composed dominantly of quartz, orthoclase, plagioclase, biotite, and hornblende, with magnetite and

[1] Iddings, J. P., Igneous rocks, vol. 2, p. 451, 1913.

apatite as accessories. Quartz occurs in rather abundant anhedral grains. Plagioclase slightly dominates over orthoclase; it ranges from oligoclase to andesine in character and shows carlsbad, albite, and pericline twins, many with zonal development. Biotite occurs in brown, strongly pleochroic shreds. The hornblende is green, pleochroic, and some of it is twinned. The rock is intermediate in character between granite and quartz diorite, and is classified as quartz monzonite. The adjoining sediments have been only slightly affected structurally by the intrusion, but in the vicinity of the contact they are injected with numerous dikes of rhyolite porphyry and fine-grained granite and show considerable silicification and pyritization. The intrusive area adjacent to the glacier of the West Fork of the Susitna is composed of a quartz-biotite diorite, with phases that have been mineralized with pyrite. The rock throughout this intrusion is massive.

AGE OF THE GRANITIC INTRUSIONS.

The granular intrusives of the Broad Pass region mark a period of batholithic invasion of unknown duration, but of notable development in Tertiary time, as indicated by the presence of both granite and diorite cutting Tertiary (Eocene) sediments. The massive character of much of the igneous material points also to late intrusion, but the gneissoid structure of some of the intrusions would seem to indicate that these occurrences are somewhat older than the massive ones. It might be argued also that because the intrusives are generally quite massive they came to place after the last period of intense folding to which the Alaska Range was subjected, the period of post-Eocene deformation, according to Brooks,[1] yet it must be remembered that bodies of resistant rock, such as igneous batholiths, may be involved in regional deformation without development of secondary structures. Attention has already been called (p. 55) to the belt of mica gneiss near Butte Lake and to the belief that this represents an older intrusive body, probably of Mesozoic age.

Granitic intrusions are prominent throughout the Alaska Range and are widely developed in southern and southeastern Alaska, as well as north of Tanana River. The evidence gathered by different workers goes to show that these occurrences are not all the result of a single period of intrusion, but rather of a succession of periods ranging possibly from Jurassic or earlier onward into Tertiary time.

GRANITE PORPHYRY.

East Fork of Jack River rises in a belt of granite porphyry and exposes fine sections of this rock in its upper canyon-like valley. The

[1] Brooks, A. H., op. cit., p. 118.

area lies within a large granitic batholith, adjoins a great body of acidic lavas and probably represents a special phase of the granitic magma. The rock is remarkable for the large size of its feldspar phenocrysts, its uniformity, and its great areal extent.

The granite porphyry was examined in greatest detail in a canyon carved by East Fork of Jack River between Seattle Creek and Brushkana Creek. It here forms great vertical cliffs, a hundred feet or more in height, of very striking aspect due to the abundance of white orthoclase crystals exposed on the surfaces. The feldspars, which average an inch in length though the largest measure 2½ inches, are thickly set in a coarse ground of greenish aspect, composed of quartz, the largest pieces of which are one-fourth inch in diameter, biotite flakes, and dark altered hornblende. The rock is decomposed and crumbles under the hammer; on its surface the feldspars are more resistant than the groundmass, standing out as prominent white areas with crystal outline. The stream bed is covered with feldspar fragments, crystals broken by weathering. Small biotite flakes are included in zones about the periphery of many of the phenocrysts. The rock carries nodular segregations, the largest 6 inches in diameter, of fine-grained biotite granite. In places the feldspar phenocrysts are especially abundant, predominating areally over the groundmass. Under the microscope the groundmass of a typical specimen showed quartz, orthoclase, and acidic plagioclase, more or less altered, biotite partly changed to chloritic material, and a little brown hornblende.

The granite porphyry is cut by a few dikes of rhyolite porphyry and bluish-gray fine-grained andesitic rock. The relation of the granite porphyry to the adjoining granite is not certainly known, but the line of demarcation is apparently well defined and suggests injection of the porphyritic rock subsequent to the formation of the granite. The belt was not traced westward to its termination because of difficulties of travel in that direction.

ACIDIC LAVAS.

At the head of Seattle Creek, and near the belt of granite porphyry just described, the granite is associated with great masses of effusive igneous rocks. Time did not permit their areal delimitation in the field, as they are intricately interassociated, so they are mapped together as "acidic lavas." Smaller areas of similar rocks were observed near the head of Brushkana Creek and north of Soule Creek. Further work would probably disclose still other flows within the general area occupied by the same batholith, and detailed petrographic study of more abundant specimens would undoubtedly yield other rock types.

Microscopic study shows the lavas to consist mainly of rhyolite, trachyte, and andesite. The rhyolite is of at least two types. The most abundant phase is a reddish rock showing flow structure in alternate layers of red and buff color. In the hand specimen small crystals of quartz and feldspar may be distinguished. Under the microscope the rock is seen to be composed of phenocrysts of quartz, orthoclase, and plagioclase set in a fine-grained crystalline ground mass composed of an interlocking mass of quartz and kaolinized feldspar with a little magnetite and sericitic material. Quartz is the most abundant of the phenocrysts; it shows well-formed hexagonal and quadratic forms with here and there a corroded edge or corner. Orthoclase in euhedral to subhedral kaolinized tabular crystals predominates over plagioclase, which is not exactly determinable but of acidic character. A second and less extensive phase of the rhyolite was observed near the center of the largest lava area. This is a cream-colored rock showing on broken surfaces a conspicuous sprinkling of small, clear, quartz crystals. Under the microscope these quartz phenocrysts show both hexagonal and quadratic forms, with edges considerably rounded by corrosion; they are associated with orthoclase in tabular, rhombic, and triangular plates, some of which show twinning according to the Carlsbad law. The phenocrysts are set in a gray, fine-grained groundmass resolvable with difficulty under the highest power. Near their northeast border the lavas are associated with outcrops of a coarser-grained porphyritic rock showing well-formed crystals of quartz and feldspar in a granular groundmass of greenish aspect. The microscope shows the feldspar to be largely orthoclase and the groundmass to consist of a mosaic of quartz and feldspar carrying a little decompositional material. The rock is a rhyolite or granite porphyry and is judged to be a textural variant of the rhyolite.

The trachyte is typically a dark-gray rock, showing small feldspar crystals in a dense groundmass. Under the microscope the feldspars are seen to include both orthoclase and acidic plagioclase in nearly equal proportions, and the groundmass is resolved into a fine-grained mosaic composed chiefly of feldspar, with no quartz discernible. Ferromagnesian minerals are not notably developed. One specimen, resembling the trachyte in other particulars, carries in addition some small quartzes and seems to represent a transition into rhyolite.

Andesite is not so widespread as the more acidic lavas; it was noted at one point only—near the center of the principal area of lavas. It is a heavy dark-colored rock, in which laths of glassy striated feldspars are recognizable in a dark-blue fine-grained groundmass. Under the microscope the rock appears strikingly

fresh. The dominant phenocryst is plagioclase, running into andesine in composition; it occurs in laths, rhombs, and tables and shows albite, Carlsbad, and pericline twinning. Orthoclase in subordinate amount occurs in tabular crystals, and the section contains a few euhedral crystals of augite. The groundmass is an aggregate of finely developed clear plagioclase laths, whose interstices are filled with pale-green augite grains and crystals.

The nature of these rocks indicates an origin in the form of effusive lavas. Their contact with the granite was not directly observed, but the general relations imply that they were poured out after the consolidation of the granite. They probably mark the close of the batholithic invasion.

OLIVINE GABBRO.

An intrusion of olivine gabbro invades the limestone-argillite series southwest of Nenana Glacier. The mass was examined in detail only near its western border, but the characteristics noted there probably hold for the entire batholith. The rock is hard, tough, and presents a weathered surface of reddish aspect. It is medium grained, and on fresh break shows an oily luster and red-gray tinge. Close examination of hand specimens reveals abundant glassy feldspars, associated with a brownish pyroxene and rather prominent plates of reddish biotite. At one point a coarse pegmatitic phase of the gabbro was noted, in which the pyroxene crystals attain a length of 2 to 3 inches.

Under the microscope the average rock is seen to be remarkably fresh. It consists essentially of a mass of plagioclase laths, carrying monoclinic pyroxene, biotite, olivine, and brown hornblende. The plagioclase is notably fresh and shows albite, Carlsbad, and pericline twinning; numerous measurements indicate it to be mainly labradorite. The monoclinic pyroxene is faintly greenish to pinkish in color and nonpleochroic. It occurs in stout, irregular crystals with borders more or less penetrated by the feldspars, and much of it is partly altered to fringing masses or included shreds of brown hornblende. Its highest observed extinction is 39°. The biotite is strongly pleochroic, from reddish brown to straw colored, and forms shreds and comparatively large, irregular plates inclosing the other minerals poikilitically. In places it shows partial alteration to pale-green chloritic material. The olivine occurs in grains of greenish color, showing the prominent cracks characteristic of this mineral; many grains contain areas and stringers of green serpentine, into which it is altering, accompanied by magnetite. Brown hornblende is present in small irregular crystals sparsely scattered through the section, in addition to that contiguous to the pyroxene.

The rock is in many respects similar to the olivine-pyroxene monzonite described by L. M. Prindle[1] from the Kichatna Valley in the Mount McKinley region, which is characterized by the minerals of the rock here discussed, together with more or less orthoclase.

No definite evidence is afforded as to the age of the gabbro intrusion; it is regarded, however, as the result of the general intrusive period that was dominated by granitic and dioritic invasions.

AMYGDALOIDAL ANDESITE.

About 6 miles above the mouth of Revine Creek an important flow of amygdaloidal andesite lies within the Cantwell formation. This area was not visited by the geologic party, and its limits are not precisely known. Its location and the character of the rock are based on information and specimens collected by J. W. Bagley, of the topographic party.

In hand specimens the rock shows a light grayish-green fine granular groundmass, carrying abundant rounded to elliptical amygdaloidal cavities, averaging 2 milligrams in diameter and partly to wholly filled with dark-green serpentine of radiating texture. Under the microscope the rock is seen to consist of an aggregate of altered feldspar laths set in green augite, changed almost completely to chloritic material. Feldspar phenocrysts of undeterminable character are scattered through the groundmass, together with grains of magnetite and a little ilmenite. The vesicles carry radiating aggregates of serpentine fibers. The feldspars, though not exactly determinable, are fairly acidic, and the rock accordingly is called an andesite rather than a basalt.

The age of the flow is probably late Tertiary, since it occurs within the Cantwell formation, of Eocene age.

DIKE ROCKS.

Dikes are fairly abundant in the sedimentary formations of the Broad Pass region and in the main seem to be genetically connected with the granitic intrusives. These bodies themselves also in many places carry dikes that probably represent the last expression of the intrusive period. On the whole the dike rocks of the area studied are distinctly acidic, few reaching the basicity of an andesite. The subject can be treated in the most general way only, because the reconnaissance character of the field work permitted the examination of but a subordinate number of the dikes actually present.

[1] U. S. Geol. Survey Prof. Paper 70, pp. 141–143, 1911.

The Triassic (?) slates are intruded by both acidic and basic dikes, the basic ones less abundant and of andesitic character. On a tributary of Deadman Creek, about 6 miles west of lower Butte Creek, a number of small pegmatite dikes are exposed in the stream bluff. In a fragment of the pegmatite were noted brown garnet, biotite, emerald-green mica, and specks of arsenopyrite. A mile southeast of this locality, and near the contact between slate and an intrusive body of quartz monzonite, the sediments are considerably metamorphosed and carry narrow dikelike intrusions of fine-grained biotite-hornblende granite, a fine-grained dioritic phase of the same rock in places porphyritic, and rhyolite porphyry, with well-crystallized quartz phenocrysts, the largest one-sixteenth inch in length, set in a rather dense cream-colored groundmass. On upper Wickersham Creek, a third of a mile above its largest tributary, a dike of hard massive dioritic rock crosses the stream, causing conspicuous falls. The rock carries numerous patches of pyrite and is composed of green hornblende, orthoclase, acidic plagioclase, and quartz, with biotite, shredded sericite, and tourmaline needles.

The Jurassic (?) slates of Jack River are injected by dikes of rhyolite porphyry, which are especially abundant near the granite contact east of Jack River, where the largest were 4 feet in width. No basic dikes were seen to cut this formation.

The belt of gneiss that extends southwestward from Butte Lake is intruded by dikes of white alaskitic rock and of andesite porphyry, which are apparently an expression of the diorite body that adjoins the gneiss on the south.

The limestone-argillite formation southwest of Nenana Glacier carries interbedded lenses and dikes of rhyolite porphyry and of medium to fine grained diorite that contains much biotite and presents pegmatitic phases with lath-shaped biotites, the largest of which are an inch in length.

The Cantwell formation at the head of Wells Creek is cut by abundant dikes of rhyolite porphyry that show well-defined phenocrysts of quartz and feldspar in a greenish ground. Under the microscope this rock is seen to be composed of phenocrysts of corroded quartz, irregularly rhombic orthoclase, acidic plagioclase, and hornblende almost completely altered to chloritic and serpentinous material in a groundmass of quartz and feldspar, most of it graphically intergrown. Bowlders and cobbles of gray, fine-grained diorite porphyry were noted in some abundance in the bed of Wells Creek, but this rock was nowhere seen in place. Diabase dikes were not found in those portions of the Cantwell examined, though Brooks[1] noted their presence in this formation west of Nenana River.

[1] Brooks, A. H., op. cit., p. 79.

In the large granite area including Deadman Mountain there are scattered outcrops of fine-grained diorite and rhyolite porphyry, which seemingly represent dikelike intrusions that closed or followed the intrusive period. A specimen of rhyolite porphyry collected near the head of Seattle Creek shows a conspicuous sprinkling of quadratic and hexagonal quartzes with white rectangular feldspar in a dense greenish groundmass, the rock having an aspect quite similar to that occurring in the Wells Creek area of the Cantwell formation. The granite porphyry adjoining the granite batholith also carries dikes of rhyolite porphyry that show small well-formed quartz and feldspar crystals and here and there also a dike of bluish-gray fine-grained andesitic rock.

STRUCTURE.

The known structural features of the formations in the Broad Pass region have been described in the preceding pages, but it still remains to consider these features together and so far as possible to show their relations. The structure in this region is difficult of interpretation, for it is complicated by masses of igneous rock that have invaded the sedimentary formations and interrupted their continuity; it is rendered still more complex and obscure by the large areas of unconsolidated deposits that cover most of the contacts between formations.

The sedimentary formations of the Alaska Range between Broad Pass and Susitna River and those of the region farther south lie in belts that extend in an easterly direction and that are approximately parallel to the range itself. (See Pl. II, in pocket.) For the most part the beds that compose these belts are closely folded, the axes of the folds being parallel to the axis of the range, yet locally they show open folding, and it will be seen from sections A–B and C–D on Plate II (in pocket) that the axial planes of the folds are not parallel but in some places dip to the south, in others to the north.

The Alaska Range in the vicinity of Broad Pass has a synclinal structure. On the north[1] and south (Pl. II, in pocket) Paleozoic or older formations are exposed; in the heart of the range only the gently folded Cantwell formation appears. Probably the simpleness of this structure is more apparent than real, however, for extensive faulting has affected other parts of the range, and, in fact, there is evidence that in this region the southern border of the Cantwell formation is a fault scarp. Eastward from Nenana River the folds of the Cantwell become more compressed, but the gen-

[1] Capps, S. R., The Bonnifield region, Alaska: U. S. Geol. Survey Bull. 501, pl. 2, 1912.

eral synclinal structure of the formation is maintained to the Yanert Fork Glacier at least. The structural relations of the formations south of the Nenana-Chulitna Valley are only imperfectly known, but as indicated on the geologic map and sections (Pl. II, in pocket), they are characterized by a northeastward trend and by close folding, with steeply dipping axial planes.

GLACIATION.

By Joseph E. Pogue.

DEVELOPMENT OF GLACIERS IN THE ALASKA RANGE.

Since the uplift of the Alaska Range in post-Eocene time, that mountain system has become the seat of active glaciation. This process reached its maximum intensity at a time when mountain glaciers on the south side of the range were so abundant and large that they coalesced into vast piedmont ice sheets which covered all but the highest of the front range of the mountains. At present the glaciers are receding and glacial activity is diminishing, though the higher and more rugged parts of the range are still undergoing glaciation. The Broad Pass region not only exhibits throughout unmistakable evidence of former transgression of ice over much of its area, but in its northern portion it still carries large and active glaciers.

PRESENT GLACIERS.

Yanert Fork, Nenana, and Susitna rivers head in large glaciers that fill great valleys and reach back into inaccessible portions of the Alaska Range. In addition to these prominent large-valley glaciers there are many small remnantal glaciers that occupy hanging valleys tributary to the main glaciers or that lie in the upper parts of cirques.

The Yanert Fork Glacier was not visited by the geologic party, but was surveyed topographically and its form and size are well shown on the topographic map (Pl. I, in pocket; see also Pls. V, *B*, p. 14, and VI, p. 16). In type it does not differ essentially from the glacier of the West Fork of the Susitna, described on page 67. It forms the source of Yanert Fork, which runs for miles in braided channels over a broad flood plain built up of rock débris supplied by the glacier.

The Nenana (formerly called the Cantwell) Glacier was examined only at its frontal margin. It descends from rugged mountains and abuts against a low rounded ridge, which was once overridden by the ice, but which now deflects its course westward to a place where it terminates in a débris-covered slope from which Nenana River

springs. In the depression that borders the obstructing ridge on the east a low wall of ice forms a spillway from the main channel and feeds a small stream. (See Pl. VIII, *B*, p. 22.) Though time did not permit a detailed examination, the impression was gained that the glacier is retreating.

The glacier of the West Fork of the Susitna heads in the heart of the Alaska Range and draws its supplies of ice from the perennial snows of lofty mountains. With its multitude of tributary glaciers it forms a dendritic assemblage, whose main trunk sweeps southward for about 25 miles in a graceful line of double curvature. Though it almost unites with the headward reaches of the Nenana and Yanert Fork glaciers, it differs from those bodies by contributing its waters to the Pacific Ocean drainage instead of to tributaries of Bering Sea. This glacier was examined at its lower end and viewed from its right bank 7 miles above. Its surface presents a rather uniform gradient from foot to head (about 100 feet to the mile for the lower 12 miles), and appears to be notably free from medial moraines and from topographic irregularities, such as ice falls, caused by unevenness in bedrock slope. Its lateral margin, where observed, terminates in an ice cliff that is separated from the steep valley wall by a channel or moat, partly filled with rock waste and occupied by a stream. The entire glacier for several miles above its foot is mantled with a thick covering of rock fragments, producing an extremely rough, hummocky topography and obscuring the ice from view. This débris, together with rock waste and flour incorporated in the ice itself and dragged along its bottom, is supplied to the streams that emerge from the ice front during the summer season. The abundance of this supply and the silt-laden waters point to the erosional activity of the ice, which by rasping, grinding, plucking, and undermining has worn down its channel and eaten its way headward into the heart of the highest peaks. Forward from the front of the ice, which has now withdrawn to the face of the range, stretch conspicuous lateral moraines nearly 1,000 feet in height, which mark the path of retreat of this glacier. The nature and disposition of the frontal débris suggest that the ice even now is slowly receding.

The smaller glaciers of the region require no individual description. Without observed exception they represent residual portions of more extensive ice bodies, and many present a crescentic shape with concave front, indicating incomplete nourishment and approach to dissolution. These residual glaciers are practically confined to the Alaska Range proper; in the mountains south of Nenana River few such bodies can now be found, though in sheltered spots snow banks survive the summer and would require only a slight increase in precipitation or decrease in mean temperature to become incipient glaciers.

GLACIAL DEPOSITS.

The mantle of rock débris that covers the lowlands and gentle slopes of the Broad Pass region includes unconsolidated materials in varied assortment and distribution. The character and form of these deposits indicate that they were laid down by receding ice, which once covered the entire area where such deposits are found. The most widespread of these materials is the ground moraine or till sheet that extends over the broad valleys and lowlands of the region. This sheet consists in the main of an unassorted assemblage of clays and sand, mixed with bowlders and angular pieces of rock. In the main this glacial sheet presents a gently rolling surface, dotted with lakes and traversed by sluggish streams. In many places, however, the surface is characterized by low, rounded hills and elongated moundlike masses, which represent morainal material dumped at the margin of the retreating ice. In Broad Pass, near Jack River, there are long sinuous mounds of glacial material, approximately parallel and extending northeastward. Though not accessible for detailed study, these bodies were undoubtedly shaped by the ice and indicate the direction of ice movement at this locality. (See Pl. III, *A*, p. 8.) In the smaller and higher valleys the drift invariably shows a rolling haphazard surface, which indicates deposition at a later stage in the glacial epoch, when the ice had receded from the piedmont slopes but still occupied these tributary valleys. Outward from most of these valleys extend well-defined lateral moraines, which mark the course of the valley glaciers that once filled them; the existing glaciers have invariably left such paths of their retreat. The drift sheet in general is associated with more or less stratified gravels, sands, and silts that result from the assortive action of water and that represent materials supplied by the ice but laid down about its margin as outwash plains or valley trains. The relative abundance of these fluvioglacial deposits is not known, as in many places they are covered by vegetation. Similar deposits are now being formed on river flood plains by waters opaque with glacial sediments.

GLACIAL EROSION.

The erosive effects of the ice are of two diverse kinds—those produced above the ice, which give rise to sharp, rugged topography, and those produced beneath the ice, which result in curved surfaces and rounded forms. No part of the Broad Pass region is free from one or the other kind of glacial erosion, for even the drift rests on an ice-scoured floor and the highest peaks owe their form to ice attack. The topographic map (Pl. I, in pocket) strikingly shows the angular outline of the higher mountains in contrast to the subdued and rounded relief of the lower portions of the area.

The mountain upland owes its rugged character to the development of glacial cirques—amphitheater-shaped basins of characteristic outline—each lying at a valley head and representing a catchment area of a former or existing glacier. These basins were carved by the ice itself at the beginning of glaciation, and some of them are not at the heads of preglacial valleys, for a cirque may develop in any slight depression where snow gathers. As glaciation proceeds and becomes more intense, the cirques are enlarged laterally, subsidiary cirques are formed, adjacent cirques merge, and cirques on opposite slopes finally intersect. In this way the glaciers literally eat their way headward into the mountains, leaving, if the glacial period continues long enough, no part of the upland free from their attack.

In the Broad Pass region the mountains are dominated by cirque topography, and so little time has elapsed since the development of these forms that subsequent erosion has scarcely modified their outlines. The most conspicuous feature of the landscape, however, is not the depressions themselves but the sharp ridges and pinnacles that remain between impinging cirques. Here topographic forms of the most rugged character abound—comblike and knife-edge ridges, sharp peaks, sheer cliffs, and steep declivities. These forms vary in contour, to be sure, according to the nature of the rock composing them, for although cirques are equally developed in mountains composed of different rocks, the formation being dependent only on altitude and precipitation, it is in massive rock, such as granite, that the most intricate and rugged relief is produced. The sharp ridges of the glaciated mountains form in horizontal plan an involved and branching pattern; in vertical section their roughly concordant elevation is frequently interrupted by U-shaped saddles or cols due to the intersection of two opposing cirques, and by higher peaks, some of them almost pyramidal in shape, the whole representing a cirque-scalloped remnant of a more extensive mountain. (See Pls. IV, *B*, p. 12, and V, *A*, p. 14.) The floors of the ice-abandoned cirques are now covered with rock débris, and here and there a lake, high perched in such a depression, remains to indicate the lack of erosion since the departure of the ice.

The topographic forms developed by the abrasion of slowly moving ice are very conspicuous in the Broad Pass region. The most common effect is the rounded outline, or U shape, imposed on the valleys by the ice streams that once traversed them. (See Pls. IV, *A*, p. 12, and V, *A*, p. 14.) The cross sections of these valleys are markedly different from the usual angular or V-shaped outline produced by normal stream erosion, a shape notably lacking in this region. Second in importance to these ice-shaped valleys are truncated spurs whose summits have well-defined triangular faces. These

forms are likewise due to moving ice that impinged on lateral ridges and ground them down to a concordant plane. They furnish graphic and unmistakable evidence of ice transgression. In general, they occur in series, and a finely developed set forms the southern wall of Broad Pass. (See Pl. VII, *A*, p. 18, and the topographic map, Pl. I, in pocket.) A third feature illustrating the abrading effect of the ice is the so-called hanging valley, a lateral tributary valley that ends at a level above the bottom of the trunk valley and that results from overdeepening of the larger channel by the ice. Many of these valleys contain small streams which cascade in beautiful ribbon-like falls over the steep slopes to the main valley floor. Valleys of this kind are typically developed along upper Jack River. From such well-defined valleys there are gradations in size into hanging cirques, whose fronts are intersected by the main valley. Rounded rock surfaces are common throughout the region and require no notice here other than the observation that they locally carry striæ cut on them by ice-dragged fragments.

EARLIER GLACIATION.

The deposits and erosional forms just described indicate that glaciation, which is still in progress in the higher mountains of the Alaska Range, was formerly more severe and extensive and involved the whole Broad Pass region. The uplift of the Alaska Range in post-Eocene time established conditions favorable to glaciation. With increased precipitation or decreased temperature, or both, the mountain glaciers increased in size and number and, on emerging from the front of the range, coalesced in a piedmont ice sheet that was augmented by smaller glaciers that rose in the front ranges of the mountains until it covered the entire lowlands and overran the lower mountains to an elevation of at least 4,600 feet, the highest observed point of glacial erosion on a faceted spur south of Broad Pass. The region affords no evidence of more than one ice transgression. Certainly no conspicuous transgressions followed the major one, and preceding less extensive advances would be obscured by the maximum advance. The period of maximum advance is not precisely known, other than that it followed post-Eocene deformation and preceded the present waning glaciation; the lack of erosion on ice-shaped surfaces, however, points to a short lapse of time since their development. After the ice sheet reached its maximum development the climate became milder and the ice withdrew from the lowland and the piedmont slopes. Whether this withdrawal was continuous or whether it proceeded at intervals is not known, though such change would probably not be without fluctuations. Glaciers persisted in the mountains after the piedmont ice had dis-

appeared, and a transition was thus effected to the present epoch of high-level glaciation.

The movement of the ice is not known in detail, but there is evidence that one part of the sheet moved southwestward through Broad Pass, whereas in the eastern part of the region the movement in general was southward. The topography of the region and the disposition of the present glaciers would seem to indicate that the ice advanced from two centers—one in the high mountains of the Mount McKinley group and the other amid the Cathedral-Hayes assemblage. During maximum glaciation the major lobes and the subordinate intermediate ones merged into one vast ice sheet whose movement was determined by the topography of the country in front of the mountains, but during the advance and retreat of the ice the lines of movement probably radiated from these two centers. During all stages of glaciation there were undoubtedly many conflicting ice currents, especially about the borders of the mountain masses, of which a single example is furnished by south-facing faceted spurs between the present glaciers of the West Fork and the Middle Fork of the Susitna, which indicate a transverse movement here, at the very front of the Alaska Range. The maximum thickness of the ice sheet, judged from the height reached by glacial erosion on the mountain slopes, is believed to have been more than 2,200 feet, a figure obtained by direct measurement of the height of certain faceted spurs south of Broad Pass.

CHANGES IN DRAINAGE DUE TO GLACIATION.

The drainage of the Broad Pass region, which was established by the uplift of the Alaska Range and conditioned by the topography then formed and by the structure and character of the underlying rocks, has been profoundly affected by subsequent glaciation. These subsequent changes in the drainage pattern are due (1) to deposits of glacial material left after the retreat of the ice, (2) to changes in topography due to erosion by ice, and (3) to the topography of the original surface of the ice itself.

The deposition of glacial drift over the low-lying portions of the Broad Pass region has produced areas marked by abundant lakes, by undrained and sluggishly drained tracts, and by streams that are errant, meandering, and discordant to the structure and lithology of the underlying rocks. The drainage has been lifted, so to speak, from its former bed and superposed on this mantle of unconsolidated material, so that now amid a region of high and rugged mountains a kind of drainage prevails that is normal only to regions of mature and subdued topography. This condition is locally striking, but is not of wide effect, for few of the larger drainageways have

been entirely diverted from former courses by morainal deposition alone. The effect has rather been to convert an active stream into a sluggish one, a well-drained valley into a marsh, and only in exceptional places to reverse or change the direction of flow. Where a reversal or change in direction of drainage has apparently taken place the process seems, in most instances at least, to have been complicated by the manner of retreat of the ice, the disposition of the ice itself rather than deposits left by it having been the conditioning factor in directing postglacial drainage. An example of this condition is formed by the anomalous course of Butte Creek southward across the Triassic (?) slate formation, with its abrupt eastward sweep into the Susitna, in contrast to preglacial Butte Creek, which probably flowed southwestward from Butte Lake into Deadman Creek. Morainal damming alone seems incompetent to have caused this change, for the present stream cuts through a solid rock barrier of Triassic (?) slates at an elevation greater than the morainal deposits that form the divide between Deadman Creek and Butte Creek. The presence of ice at this locality, and especially the fortuitous manner of its retreat, are therefore assumed to have influenced the location of the present course of Butte Creek.

Erosion due to ice abrasion has modified stream gradients and developed local features, such as falls and rapids, but with the exception of Nenana River it has apparently had little broad effect on the drainage pattern. Hanging valleys with their frontal cascades form striking and picturesque examples of stream disturbance due to glacial erosion. The drainage of the upland regions, characterized by cirques, occupies depressions formerly filled with ice, but whether these lines were developed by the ice, in which event the present drainage is not superimposed on the preglacial one, or whether the ice merely deepened valleys initiated by normal processes of erosion, are questions that can not be satisfactorily answered here. The presumption is that both conditions are in part fulfilled in the Broad Pass region.

The course of Nenana River northward through the Alaska Range instead of southwestward through Broad Pass into the Chulitna basin is so discordant to structure and preglacial topography that it must have been due to unusual conditions. It is now well known that glaciation was and still is more intense on the seaward face of the Alaska Range than on its inland slope, a fact shown clearly on the geologic map of the Mount McKinley region.[1] The thick accumulation of ice in the Broad Pass region is thought to have found a northward overflow through a depression in the Alaska Range,

[1] U. S. Geol. Survey Prof. Paper 70, pl. 9, 1911.

which it overdeepened and left invested with the present Nenana River. This explanation derives additional weight from the fact that the course of the Nenana lies halfway between two centers of ice development—the high mountains of the Mount McKinley group and those of the group containing Cathedral Mountain and Mount Hayes, so that on the recession of the ice the eastward and westward drainage was probably blocked by waning ice lobes. Delta River, 90 miles to the east, which flows northward through Delta Pass, forms an example analogous to the Nenana, and a similar explanation has been advanced for its discordant course.[1] Two other explanations of the courses of these two rivers are possible—first, that they are antecedent streams, whose courses were maintained during the elevation of the Alaska Range, and, second, that they are due to headward erosion of streams which began on the north side of the range. These explanations, however, seem less adequate to meet the field condition than the one involving glaciation.

The principal changes in drainage caused by glacial deposition and erosion by ice have been indicated, and the suggestion has been made that some of these changes have been in part conditioned by the surface configuration of the original ice sheet and the manner in which this sheet receded. On the whole, the topography of the ice has apparently played an important part in determining the course of the present streams, though the precise way in which it exerted its influence and the places where it was most effective are difficult to ascertain. Inasmuch as the present drainage was developed at the edge of a waning ice sheet and was left in the path of its receding border, it appears that the disposition of the ice at its different stages must have fixed or controlled the position of the drainageways in many places where the original topography was insufficient to maintain control. The course of Butte Creek was apparently so determined. The explanation advanced to account for the northward course of the Nenana involves this principle. The diverging paths of Nenana and Susitna rivers, which head within a few miles of each other, are due to the fact that their sources were formerly more widely separated by an ice lobe of which their respective glaciers are remnants. The course of Jack River northward into the Nenana instead of through Broad Pass is probably due to the extension in the past of the glaciers near Mount McKinley across the upper Chulitna Valley, where they formed a barrier to southwestward drainage.

[1] Moffit, F. H., Headwater regions of Gulkana and Susitna rivers, Alaska: U. S. Geol. Survey Bull. 498, p. 51, 1912.

GEOLOGIC HISTORY.

The geologic history of the Broad Pass region can only be sketched, and very imperfectly, for the facts at hand are too meager to warrant a fuller or more detailed account. The first event of the geologic record, so far as is now known, is the deposition of argillaceous and calcareous sediments in Devonian time. These beds of Devonian slate, schist, and limestone are more highly altered and more intricately folded than the other sedimentary formations of the region, and they were probably folded and subjected to erosion before they were covered by later formations.

The next major event is in doubt. Apparently the lavas that form the mountains south of Butte Creek were poured out at this time, but the Triassic (?) slates of Butte Creek may have been deposited before the volcanic rocks were ejected. Facts bearing on the relative ages of these formations have already been given and need not here be repeated. What appears to be the upper part of the lava flows in the vicinity of the Roosevelt Lakes contains water-laid tuffs, and the near-by Triassic (?) sediments also contain tuffaceous beds. This evidence is interpreted as indicating an interval between periods of volcanic activity and normal sedimentation, during which the clastic material produced during volcanic outbursts and that due to erosion of a land surface were intermingled. No indication of volcanic activity during the deposition of the upper part of the Triassic (?) sediments has been found.

Little, if any, evidence is at hand to show what took place between the deposition of the Triassic (?) rocks and the group of slate, graywacke, and conglomerate on Jack River. This group is provisionally assigned to the Jurassic on rather slender evidence. The beds that composed it must have accumulated rapidly under rather unstable conditions, possibly in shallow water near a shore line. They are the youngest sediments of the region assigned to the Mesozoic. They were folded and intruded by igneous masses, and after being elevated were subjected to erosion for a long period, which probably extended into Tertiary time. If Cretaceous beds were ever laid down in this region they either have been unrecognized or have been entirely removed.

It is believed that when the conglomerates and sandstones of the Cantwell formation began to accumulate in early Tertiary (Eocene) time the area where the Alaska Range now rises had been reduced by erosion to a region of much lower relief than that of the present. A mountain mass, or at least a region of higher elevation, lay to the south and furnished material for the conglomerates, sands, and shales of the deposits that were being laid down along the front of the

highland, not in the sea but on a marshy lowland, possibly near the sea. Deposition of the Cantwell sediments was followed in Tertiary time by mountain-building movements that finally gave rise to the Alaska Range as we see it to-day. The Cantwell and all the older formations were intruded by large masses of igneous rock, granite, diorite, and related types, and were folded together and elevated, permitting the revival of vigorous erosion.

It is not known when all the different igneous rocks of the region invaded the sediments. Probably intrusion went on intermittently throughout all the time between the deposition of the Devonian formations and the elevation of the Alaska Range. It is known, however, that widespread crustal movements and the intrusion of large masses of igneous rock took place some time after the Middle Jurassic epoch. According to Brooks,[1] the great batholiths of the Coast and Alaska ranges and of the Talkeetna Mountains were then intruded. Nevertheless it does not appear that the extent of Tertiary intrusion has been fully realized. The revival of the processes of erosion that began with the elevation of the Alaska Range led to the blocking out of the principal topographic features seen in the range to-day, but these features have been profoundly affected by other agencies than weathering and normal stream erosion, for the elevation of the range also gave rise to conditions that led to intense and long-continued glaciation of the region and great modification of the preexisting drainage and topographic forms. These changes have been discussed more fully in the section on glaciation (pp. 66–73).

ECONOMIC GEOLOGY.

MINERALIZATION.

Geologic conditions within the Broad Pass region are of a kind commonly regarded as favorable to mineralization. Wide areas of slate, shale, limestone, and other sedimentary deposits have been intruded at different times by granitic rocks of several types. Many such intrusions in other regions have led to extensive mineralization of the invaded rocks, but the results of the field work of 1913 show that the Broad Pass region is not so greatly mineralized as our knowledge of the other features of the geology would indicate. Many contacts of igneous and sedimentary rocks were examined with considerable care, yet without finding notable mineralization. At some places there is a small amount of pyrite, and the invaded rock has suffered such changes as baking and silicification, but otherwise the intrusive rocks appear to have produced little effect.

[1] Brooks, A. H., The Mount McKinley region, Alaska: U. S. Geol. Survey Prof. Paper 70, p. 117, 1911.

No mining is carried on in the Broad Pass region. Parts of the region have been prospected, chiefly for placer gold, in a hasty and imperfect way, but the results of prospecting were not encouraging, though gold, copper, and coal have been found.[1] The men who discovered the gold placers of Valdez Creek ascended Susitna River from the mouth of Tyon River, prospecting the tributary streams on both sides of the river as they went. They found coal on a western tributary of the Susitna which they called Coal Creek, and panned gold from the gravels of Butte Creek and some of the smaller unnamed streams.

GOLD.

The gravels of Butte Creek, Wickersham Creek, and several small streams that flow into Susitna River from the west in the vicinity of Valdez Creek contain placer gold. Gold prospects have also been found on some of the small streams west of the glacier at the head of West Fork of Susitna River, but no mining has been done. An attempt to recover gold from the gravels of Wickersham Creek and one or two of its tributaries did not turn out profitably.

All these localities are in areas of slate or schist. So far as is known to the writer placer gold has not been found within the areas of igneous rock, except in places where the gravel is derived in part from neighboring sedimentary formations.

COPPER.

Copper-bearing minerals have been found in the lava flows between Butte and Wachana creeks and Susitna River and are reported from localities on the upper part of Chulitna River. A rather large vein of chalcopyrite was found several years ago south of the eastward bend in Butte Creek. This locality was not visited by the Survey party, but a specimen of the ore furnished by Mr. Peter Monahan, of Valdez Creek, shows olivine basalt carrying disseminated chalcopyrite. No effort has been made to exploit the lode.

COAL.

Coal Creek joins Susitna River 3 or 4 miles above the mouth of Maclaren River. Coal was found on this stream in 1904, but no attempt has been made to use it. Little can be said about the occurrence of coal in this locality, for neither its thickness nor the character of the rocks associated with it are known.

[1] During the summer of 1914 reports of the discovery of valuable lodes in the Broad Pass region were widely disseminated. These were described as large deposits carrying ores of low value. The place at which these lodes were found is unknown, and there has been no authoritative confirmation of the discovery.

Seams of coal only a few inches thick are interstratified with carbonaceous shale in the Cantwell formation, but they do not promise to be of commercial value.

ECONOMIC CONDITIONS.

Most of the conditions that would affect prospecting and mining in the Broad Pass region have already been discussed under the head of "Geography," but further reference to one or two of them is desirable. Transportation is the most important, and might easily be the deciding factor in determining the profitableness of a mining venture in this region. Under present conditions ordinary supplies can probably be freighted to Broad Pass from Fairbanks more easily and cheaply than from any other point. Even now some of the miners on Valdez Creek bring supplies from Fairbanks, hauling them over the ice of Nenana River. The winter route from Cook Inlet, however, should be fully as good, although the use of this route would necessitate landing freight at the head of Cook Inlet before winter sets in.

On the other hand, most of the mining equipment and supplies used on Valdez Creek will doubtless continue for a few years to be hauled from Chitina, and the lesser cost of trail breaking by this route must be taken into consideration in calculating the cost of winter freighting into the Broad Pass region.

The transportation problems of the upper Chulitna, Susitna, and Copper River regions will probably be entirely changed in the near future. Since the passage of the Alaska railroad bill the different routes from the coast to the Tanana and Yukon valleys have been surveyed and that leading from Seward to Fairbanks by way of the Susitna, Chulitna, and Nenana valleys has been chosen as the route for the first railroad to be built in Alaska by the Government.

Construction work on this road has been begun, so that there is reason for believing that the Broad Pass region will soon be one of the parts of interior Alaska most easily reached.

The Broad Pass region, considered as a whole, is timberless. The sketch map shown in figure 2 (p. 18) indicates that spruce grows only along the principal watercourses and that the higher country is without timber. It is therefore evident that both lumber and fuel must be imported if required in considerable quantity. The lignitic coal that is so abundant in the Bonnifield region north of the Alaska Range may be used, yet the higher grade coal of Matanuska Valley is more likely to be employed when railroad communication with Cook Inlet is established.

The Broad Pass region may be said to be almost unexplored so far as a knowledge of possible mineral resources is concerned. It

appears unlikely, however, that it contains important deposits of coal, for the principal coal-bearing formation of this part of Alaska is not widely developed south of the Alaska Range in this region.

Though no extensive mineralization was found here during the geologic field work of 1913, that work was not sufficiently detailed to warrant a sweeping statement as to the presence or absence of metallic deposits, particularly when the general geologic conditions appear favorable to their presence, and it is believed that a search for valuable metals may be justified.

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BULLETIN 609

THE FRACTIONAL PRECIPITATION OF SOME ORE-FORMING COMPOUNDS AT MODERATE TEMPERATURES

BY

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THE FRACTIONAL PRECIPITATION OF SOME ORE-FORMING COMPOUNDS AT MODERATE TEMPERATURES.

By Roger C. Wells.

INTRODUCTION.

SCOPE OF THE INVESTIGATION.

The experiments described in this bulletin were made to aid in elucidating the chemistry of ore deposition. They were confined to aqueous solutions at moderate temperature, and they have shown the order of solubility of the compounds of each of the classes investigated—sulphides, hydroxides, carbonates, and silicates. The solubility of most of these compounds in water is so slight that its direct and accurate determination is difficult. The literature of the subject accordingly contains many determinations of their solubility by indirect physicochemical methods, and some of these are given in this bulletin in order that they may be compared with the results obtained in the experiments here reported. Three or four complications have been met in the otherwise simple relations of solubility, namely, that sulphides may act as reducing agents, that carbonates and silicates may precipitate hydroxides, and that solids may require considerable time to assume their most stable forms.

Considered chemically, the precipitation of an ore from a solution may require only a single condition—the constituents of the ore must be present in the solution in certain forms and in concentrations above certain minima. A closer examination of this requirement, however, shows that it is conjoined with other minor requirements, all more or less related in such a way that a certain lack of one may exist if another is more than fulfilled. A statement of the relative solubility of two metallic compounds based on the final table given in this paper (p. 45) need not, for example, correspond with the order of their deposition in nature, although the solubility of an ore has a direct relation to its deposition. The solubilities presented were determined by starting with solutions containing the competing metallic

constituents in equal concentrations, whereas in nature the constituents occur in various concentrations and the deposition of ores is governed very largely by the mass law, a point that will be more fully discussed elsewhere in this bulletin.

The present experiments do not show the behavior of solutions that may exist in magmas or that may constitute magmatic exudations. Such solutions are not only at high temperature and pressure but some of them are also supposed to contain liquid carbon dioxide, chlorides, fluorides, and sulphides, together with water. As some of these compounds are mutually incompatible, the assumption that such solutions are a source of ore deposits requires a great deal of explanation, one of the first requirements being the ascertainment of groups of metallic and nonmetallic elements that can be appreciably compatible in such solutions. Though such solutions seem to have played important rôles in the deposition of certain ores, as indicated by geologic evidence, yet, as aqueous solutions at moderate temperatures form not only the solvent but the transporting medium and distributing agent of enormous quantities of metalliferous material, especially in the upper parts of the earth's crust, any generalizations that may be established with reference to such solutions will have wide application.

It is interesting to trace the cyclic courses of the various elements in the numerous operations that are going on unceasingly in the earth. The continents are elevated and eroded; the sediments consolidate and possibly fuse together anew to form new magmas; intrusions and extrusions are constantly occurring. The following quotation from T. Sterry Hunt well expresses the continuity of these processes:[1]

> We learn * * * that amid all the changes of the face of the globe the economy of nature has remained the same. We are apt, in explaining the appearances of the earth's crust, to refer the formation of ore beds and veins to some distant and remote period, when conditions very unlike the present prevailed; when great convulsions took place and mysterious forces were at work. Yet the same chemical and physical laws are now, as then, in operation; in one part dissolving the iron from the sediments and forming ore beds, in another separating the rarer metals from the ocean's waters; while in still other regions the consolidated and buried sediments are permeated by heated waters, to which they give up their metallic matters, to be subsequently deposited in veins. These forces are always in operation, rearranging the chaotic admixture of elements which results from the constant change and decay around us.

The courses of the valuable metals in these cycles, as well as those of the nonmetals most frequently associated with them, are of particular significance in respect to theories of ore deposition.

[1] Hunt, T. S., Chemical and geological essays, chapter 12, pp. 235–236, 1878.

In discussions of the origin of ore deposits the nonmetallic constituents are frequently neglected. If an ore contains more than one element the term "source of the ore" is equivocal, as it is possible that the metal may have come from one source and the nonmetal from another. The presence of the nonmetallic constituent needed to precipitate the metallic constituent may in fact explain the presence or absence of an ore at a given locality. Moreover, the proportion of such a constituent may determine the character of the ore; for example, in a solution containing iron and sulphur an excess of sulphur may yield pyrite and an excess of iron may yield pyrrhotite. This essential factor must be borne in mind in considering the mode of formation of ores. In the treatment adopted in this bulletin the constituents discussed are primarily arranged according to the nonmetallic constituent that combines with the metal, the sulphides in one group, the carbonates in another, and so on; that is, all the possible compounds of each metal are not considered together. Both arrangements have advantages. The one adopted here is at least equal in value to that followed in the older method of studying all the salts of one metal together.

In making a laboratory investigation it may happen that the methods employed do not reproduce natural conditions closely. For instance, in studying the behavior of gold, platinum, and silver, soluble salts are used in the laboratory, whereas in nature soluble salts are rarely found, and the essential problem is to determine the conditions of solution and transportation of those metals rather than their precipitation. Frequently, however, the assumption is warranted that mixtures of soluble metallic salts in noteworthy concentrations may come under the influence of precipitating agents—such as sulphides, sulphates, carbonates, and hydroxides—and be in part or completely precipitated. The precipitating action of solids will differ from that of solutions only in respect to the concentration of the precipitant available and the rate of the action, the action approaching that of an extremely dilute precipitant in solution.

In considering precipitation several elemental concepts have wide applicability, such as the law of mass action, ionization, and the constant solubility product. For the benefit of those who may not have access to detailed treatises on these subjects it seems appropriate to explain these concepts briefly, in so far as they are applicable to the present investigation, an investigation of solutions in which partial precipitation occurs. The law of mass action accounts for the equilibria occurring in the solution, the ions determine in the most general way the properties of inorganic solutions, and solubility finds its best interpretation through the solubility product.

THE MASS LAW.

The law of mass action has very wide application. Suppose that in any homogeneous system at a definite temperature there is possible a general reaction or equilibrium[1] of the type.

$$mA + nB \ldots\ldots \rightleftharpoons xC + yD \ldots\ldots$$

then, according to the law of mass action,

$$K = \frac{c^x d^y \ldots\ldots}{a^m b^n \ldots\ldots}$$

where a, b, c, d represent the concentrations of the molecular species A, B, C, D, and K is a constant, the equilibrium constant. It follows from this relation that an increase in the concentration of any substance on one side of the equation must result in an increase in the concentration of the substances on the other side and a decrease in the concentration of the other substances on the same side.

IONS AND THE SOLUBILITY PRODUCT.

This is not the place to present arguments for and against the theory of electrolytic dissociation suggested by Arrhenius in 1887. Almost every recent work on chemistry shows abundantly the fruitfulness of the conception of ions and presents the generalizations based on it.[2] Moreover, the phenomena of electric conduction warrant the assertion that the existence of ions is not only theoretically possible but is practically demonstrated.

The statement that a substance "ionizes" in solution does not mean that it ionizes completely but only that its characteristic ions appear among the "molecular species" contained in the solution and are potential factors of chemical reactions. The written symbols for ions indicate the nature of their electric charges—that is, they show whether they are positive or negative; for example, H^+, Cl^-; for of course such ions are entirely different from free atoms. Moreover, every solution must contain equivalent numbers of positive and negative ions.

As "molecular species" contained in the solution the ions as well as the molecules may be considered with reference to the mass law. Such a consideration leads to the conception of the "dissociation constant."

Thus,

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

gives

$$K = \frac{[H^+]\ [HCO_3^-]}{[H_2CO_3]}$$

the dissociation constant for the primary dissociation of carbonic acid.

[1] The sign $\rightleftharpoons$ indicates that the reaction may occur in either direction, according to conditions, and, according to the usual interpretation, equilibrium is merely the condition attained when the rate of the two opposing reactions is equal.

[2] For example, see Stieglitz, Julius, The elements of qualitative analysis, The Century Co., 1911.

With respect to chemical precipitates it was early assumed that the concentration of the nonionized dissolved portion is not changed by the presence of other salts,[1] but it has since been discovered that large deviations from this rule may be shown by moderately concentrated solutions.[2] The great number of solutions in which it holds fairly well, however, warrants its consideration, especially as it leads to a principle of even wider applicability, namely, that of the constant solubility product.

The solubility product (S. P.) is the product (result obtained by multiplication) of the concentrations of the ions yielded by the precipitate in the solution, which must be exceeded before precipitation can occur. Dr. John Johnston, of the Geophysical Laboratory of the Carnegie Institution of Washington, has suggested to me the need of a simpler term than "solubility product" for the mathematical function under discussion. The words "solubility product" merely denote a number that is a characteristic property of each specific substance. The evaluation of these numbers is one of the constant aims of chemists. There will be as many powers in this product as there are ions formed from the salt under examination. Thus for a uni-univalent salt

$$\text{S. P.} = [B]\,[A]$$

in which [B] and [A] are the concentrations expressed as gram molecules or gram ions per liter. For unibivalent salts the solubility product takes the form

$$\text{S. P.} = [B]^2[A] \text{ or } [B]\,[A]^2$$

and so on for more complicated salts.

Therefore if to a precipitate in a saturated solution a salt having a common univalent ion is added, the concentration of the other ion or ions of the precipitate will be decreased. Recent investigations have shown, however, that the effect of the addition of a common bivalent ion is insignificant.[3] It is not yet clear whether these results indicate a failure of the theory or whether, as seems more likely, correct evaluations of the ionic concentrations have not yet been obtained. However, though in many solutions the relations are still considered only qualitatively, the more insoluble the precipitate considered the more certainly the theory appears to be substantiated.[4] An application of the principle to sulphides, hydroxides, and carbonates of the

[1] Noyes, A. A., Ueber die gegenseitige Beeinflussung der Löslichkeit von dissocierten Körpern: Zeitschr. physikal. Chemie, vol. 6, p. 243, 1890.

[2] Arrhenius, S., Ueber die Aenderung der Stärke schwacher Säuren durch Salzzusatz: Idem, vol. 31, p. 224, 1899.

[3] Noyes, A. A., and Bray, W. C., The effect of salts on the solubility of other salts: Am. Chem. Soc. Jour., vol. 33, p. 1648, 1911.

[4] Harkins, W. D., The solubility of unibivalent salts in solutions of salts of different types: Am. Chem. Soc. Jour., vol. 33, p. 1827, 1911.

heavy metals would thus appear not wholly unwarranted, and some applications of it have therefore been made in this bulletin.

Of course it remains true that if a substance with no common ion is added to a solution the solubility of the precipitate is, in general, slightly increased, for a little of it goes to form every possible new species of molecule by metathesis; and furthermore the solubility of a substance, even in the presence of a common ion, may be greatly increased under special conditions on account of the formation of complex ions.

FRACTIONAL PRECIPITATION.

PREVIOUS INVESTIGATIONS.

Most of the separations made in analytical chemistry depend on pronounced differences in solubility and the use of an excess of reagent, but in geochemistry we have to consider associated substances whose solubility may differ but slightly and whose formation was due to fractional precipitation. A fractional precipitation is one in which only a part of the dissolved substances pass from solution to solid.

The theoretic side of fractional precipitation was treated extensively by Berthollet over a century ago. As regards fractional precipitation Berthollet was correct in contending that the composition of the precipitate might be indefinite, and Proust's view as to the definite composition of the precipitate was correct in regard to pure simple chemical compounds. Berthollet held that the fundamental factors in chemical reactions are cohesion, elasticity, and mass relations, governing, respectively, solubility, volatility, and precipitation.

Fractional precipitation of the rare earths has long been familiar to chemists. In this way the constituents of the gadolinite earths were separated by Mosander;[1] praseodymium and neodymium were separated from the cerite earths by Welsbach; the constituents of the yttria earths were separated by Crookes;[2] and the sulphide of polonium by Curie.[3] Debus,[4] in 1853, made quantitative experiments on the fractional precipitations of barium and calcium carbonate, and Chizynski[5] later studied the phosphates of these two metals. Chroustchoff and Martinoff[6] studied the precipitation of sulphates and chromates by a barium salt and Küster and Thiel the fractionation of bromides and thiocyanates by silver nitrate.[7] Recently Golblum

[1] Mosander, C. G., On yttria, terbium, and erbium: Philos. Mag., 3d ser., vol. 23, p. 252, 1843.

[2] Crookes, William, On the methods of chemical fractionation: Chem. News, vol. 54, pp. 131, 155, 1886.

[3] Curie, Sklodowska, Radioactive substances: Chem. News, vol. 88, p. 146, 1903.

[4] Debus, Heinrich, Ueber chemische Verwandtschaft: Liebig's Annalen, vol. 85, p. 124, 1853.

[5] Chizynski, Anton, Ueber die chemische Massenwirkung: Annalen der Chemie und Pharmacie, Suppl. Bd. 4, p. 226, 1865.

[6] Chroustchoff, P., and Martinoff, A., Des coefficients d'affinité chimique: Compt. Rend., vol. 104, p. 571, 1887.

[7] Küster, F. W., and Thiel, A., Ueber Gleichgewichtserscheinungen bei Fällungsreaktionen: Zeitschr. anorg. Chemie, vol. 33, p. 129, 1902.

and Stoffella[1] have studied the system involving lead carbonate and chromate.

The advantage of studying fractional precipitation for a theory of ore deposits is that the results show the net effect of all the factors that enter into play, including even unsuspected factors. Thus, if the salt of one metal is more hydrolyzed in solution than another, or if a metal has a tendency to form basic salts, the effect will be manifest in the fractionation.

An objection that may be made to many laboratory experiments is that chemical precipitates are formed instead of natural minerals. For some purposes this objection is valid; for others not. In general such experiments will shed light on the relations to be expected in the formation of minerals. In fact in many experiments it has been shown that in the course of a few hours the precipitate alters even at ordinary temperature into the mineral, as does lead sulphide.[2] In other experiments the rate of alteration is very slow, as Allen and Crenshaw have shown for zinc sulphide,[3] and solubility determinations are needed for the minerals as well as for the amorphous precipitates. I have, however, found, in every experiment in which the effect of time has been noted, that when equivalent quantities of two metallic salts are taken the experiment shows almost at once which of the two metals forms the more insoluble compound. There may be a decrease in solubility with time or a relative change in the solubilities on account of the very gradual development of the most stable compounds, but in no experiment did the metal first precipitated in excess later become the more soluble.

METHOD OF EXPERIMENTATION.

The metallic compounds will be discussed in the order of their solubility—sulphides, hydroxides and oxides, carbonates, bicarbonates, and silicates.

The procedure in the experiments on fractional precipitation was simple. A dilute solution containing two metallic salts in equivalent quantities was precipitated by reagent enough for one metal only. After a time an aliquot part of the mother liquor was analyzed and the composition of the precipitate was determined by difference. In some experiments the proportions were varied slightly, as noted.

Since the quantities of salts used are frequently expressed in equivalents a table has been prepared to assist in making conversions from units of weight to "equivalents." An equivalent is the molecular

[1] Golblum, H., and Stoffella, G., Contribution à l'étude de l'affinité chimique: Jour. chim. physique, vol. 8, p. 135, 1910.

[2] Weigel, O., Die Löslichkeit von Schwermetallsulfiden in reinem Wasser: Zeitschr. physikal. Chemie, vol. 58, p. 293, 1907.

[3] Allen, E. T., and Crenshaw, J. L., The sulphides of zinc, cadmium, and mercury: Am. Jour. Sci., 4th ser., vol. 34, p. 358, 1912.

weight of a radicle (or atomic weight of an element that constitutes a radicle) reduced to a univalent basis. The equivalents thus calculated correspond to the usual chemical equivalents of salt radicles in aqueous solution referred to eight parts of oxygen. Of course, equivalent weights of salts may be taken in milligrams, grams, pounds, or tons, but wherever no qualification is expressed gram equivalents are always understood.

Table for computing "equivalents."

For weight given of—	Divide by—	For weight given of—	Divide by—
Ag	107.87	Mg	12.16
Al	9.033	Mn″	27.46
Ba	68.68	Na	23.00
Cd	56.20	Ni	29.34
Ca	20.03	Pb	103.59
Co	29.48	Zn	32.68
Cu	31.78	Cl	35.45
Fe″	27.92	CO_3''	30.00
Fe‴	18.61	HCO_3'	61.01
H	1.008	NO_3	62.01
Hg′	200.6	SO_4''	48.04
K	39.09	HSO_4'	97.08

SULPHIDES.

SOLUBILITY OF SULPHIDES.

As these experiments were made to determine the order of solubility of the compounds studied, it will be advantageous to present first such data as already exist on the subject.

The sulphides of the heavy metals are very insoluble. Although they are ordinarily considered quite insoluble their solubilities can be determined approximately by physicochemical methods, and, in fact it has been shown that mercuric sulphide is many thousandfold more insoluble than manganous sulphide. The solubility of the sulphides in water at 18° C. was determined by Weigel[1] by the conductivity method, but the determination of the solubility by this method is complicated by the fact that the exact nature of the dissolved substances must be known, and as the sulphides produce solutions differing in alkalinity the method could hardly be expected to yield more than mere approximations to the true solubility.

[1] Weigel, Oskar, Die Löslichkeit von Schwermetallsulfiden in reinem Wasser: Zeitschr. physikal. Chemie, vol. 58, p. 293, 1907.

Solubility of the sulphides of the heavy metals in distilled water at 18° C. according to Weigel.

[Moles×10^{-6} per liter.]

Crystallized sulphides.		Freshly precipitated (probably amorphous) sulphides.	
SnS	0.14	HgS	0.05
Ag_2S	0.55	Bi_2S_3	0.35
SnS_2	1.13	Ag_2S	0.55
Galena (from precipitated PbS)	1.18	As_2S_3	2.1
Galena (Freiberg)	1.21	CuS	3.51
Cu_2S	3.1	PbS	3.6
Zinc blende (artificial)	6.63	Sb_2S_3	5.2
Zinc blende (Santander)	6.55	CdS	9.00
Greenockite (artificial)	8.99	NiS	39.87
Millerite (artificial)	16.29	CoS	41.62
Wurtzite (artificial)	28.82	FeS	70.1
Pyrite (artificial)	40.84	ZnS	70.6
Pyrite (Freiberg)	48.89	MnS	71.6
Pyrrhotite	53.6		
MnS	54.5		

The solubility products of sulphides have been determined by other investigators from time to time.[1]

For a univalent, bivalent, and trivalent metal, respectively, the solubility products (S. P.) would be:

$$S.\,P. = [M^{+}]^2\ [S^{--}]$$
$$S.\,P. = [M^{++}]\ [S^{--}]$$
$$S.\,P. = [M^{+++}]^2\ [S^{--}]^3$$

The values of the solubility products already published were collected by Bruner and Zawadzki, who also calculated them from the heat of formation of the sulphide and the electrolytic potential of the metals and of sulphur. In the table below I have placed their calculated values of the solubility products, those found by the observer noted, and finally the "solubility of the sulphide in water" calculated from the solubility product. It will be noted that the solubilities in this table are far smaller than those obtained by Weigel.

[1] Bernfeld, I., Studien über Schwefelmetallelektroden: Zeitschr. physikal. Chemie, vol. 25, p. 46, 1898. Knox, Joseph, A study of the sulphur anion and of complex sulphur anions: Faraday Soc. Trans., vol. 4, p. 48, 1908. Immerwahr, C., Beiträge zur Kenntnis der Löslichkeit von Schwermetallniederschlägen auf elektrochemischen Wege: Zeitschr. Elektrochemie, vol. 7, p. 478, 1901. Glixelli, S., Zur Theorie der H_2S Fällung der Metalle: Die Einwirkungen von Schwefelwasserstoff auf Zinksalze: Zeitschr. anorg. Chemie, vol. 55, p. 306, 1907. Lucas, R., Gleichgewichte zwischen Silbersalzen: Zeitschr. anorg. Chemie, vol. 41, p. 211, 1904. Bruner, L., and Zawadzki, J., Ueber die Gleichgewichte bei der Schwefelwasserstoffällung der Metalle: Zeitschr. anorg. Chemie, vol. 65, p. 136, 1910.

Solubility products of several sulphides and their solubility in water.

[Based on determined solubility product, if known; otherwise on solubility product calculated by Bruner and Zawadski.]

Sulphide.	Solubility product calculated.	Solubility product found.	Observer.	Solubility in water.
				Moles per liter (calculated).
MnS	7.0×10^{-16}		Bruner and Zawadski.	2.6×10^{-8}
Tl_2S	(4.5×10^{-22})	(4.5×10^{-22})	do	2.2×10^{-8}
FeS	7.0×10^{-22}	3.7×10^{-18}	do	1.9×10^{-11}
βZnS	6.0×10^{-24}	1.1×10^{-24}	Glixelli	1.0×10^{-12}
αZnS		5.0×10^{-26}	do	2.2×10^{-13}
NiS	7.0×10^{-25}		Bruner and Zawadski.	8.4×10^{-13}
CoS	1.5×10^{-26}		do	1.2×10^{-13}
PbS	2.1×10^{-28}	3.4×10^{-29}	do	1.8×10^{-14}
CdS	1.8×10^{-29}	5.0×10^{-29}	do	4.2×10^{-15}
Ag_2S	1.4×10^{-48}	4.8×10^{-53}	Lucas	2.3×10^{-18}
Ag_2S		1.5×10^{-50}	Bernfeld	1.9×10^{-17}
Ag_2S		3.9×10^{-50}	Knox	2.2×10^{-17}
CuS	7.0×10^{-45}	5.9×10^{-42}	Immerwahr	2.4×10^{-21}
CuS		1.2×10^{-42}	Knox	1.1×10^{-21}
HgS	[a] 2.0×10^{-52}	2.8×10^{-54}	do	1.7×10^{-27}
HgS	[a] 1.0×10^{-49}	6.7×10^{-48}	Immerwahr	2.4×10^{-24}

[a] Based on different heats of formation.

The order of solubility obtained from experiments on fractional precipitation should agree with the order of solubility given in the last column of the table. As a matter of fact, the agreement is excellent except for two metals, silver and cobalt. The discrepancy for silver requires explanation; that for cobalt is not surprising in view of the small difference between its solubility and those of the adjacent sulphides. The discrepancy for silver may be due to a failure of the principle of the solubility product, as silver sulphide is a unibivalent compound, or possibly to the precipitation of silver by sulphides in part as free metal. A study of the fractional precipitation of thallous sulphide would assist in deciding between these two possibilities. Weigel's series seems to place silver in its proper position, but it shows several discrepancies for other metals.

While the solubility of sulphides is under consideration attention may be paid briefly to the enormous effect of changes in acidity on the precipitation of sulphides. This effect is due to the nature of the ionization of hydrogen sulphide, the sulphide ion concentration varying inversely as the square of the hydrogen ion concentration for a given concentration of total sulphide. As is well known, the precipitability of the sulphides varies so greatly that a complete separation of certain groups is possible. Thus in an acid solution hydrogen sulphide added to a dilute mixture of the sulphates of iron and copper precipitates almost wholly copper sulphide. This is not strictly a fractional precipitation, since in an acid solution of hydrogen sulphide the concentration of sulphide is probably not sufficient to exceed the solubility product of ferrous sulphide. A fractional precipitation would be obtained with a small amount of precipitant

under conditions which would permit all the metals to be precipitated with an excess. With iron and copper sulphates, for example, a fractionation might be made with sodium sulphide, since an excess of sodium sulphide would precipitate both sulphides completely.

EXPERIMENTS WITH THE NITRATES OF COPPER AND LEAD.

The first experiments on this point showed that the composition of the precipitate depends a great deal on the manner of precipitation and time of standing. A mixture of the nitrates of lead and copper, partly precipitated with a solution of hydrogen sulphide in the cold and filtered within a short time, yielded a precipitate containing the sulphides of both metals, although copper was slightly in excess. On warming, however, copper sulphide was the chief product, being precipitated even at the expense of the lead sulphide first formed.

EXPERIMENTS WITH THE SULPHATES OF COPPER AND ZINC.

A good illustration of selective precipitation was obtained with mixtures of cupric sulphate and zinc sulphate, precipitated by ammonium sulphide. The data are given in the table below and the curves in figure 1. The evidence is very clear that even in

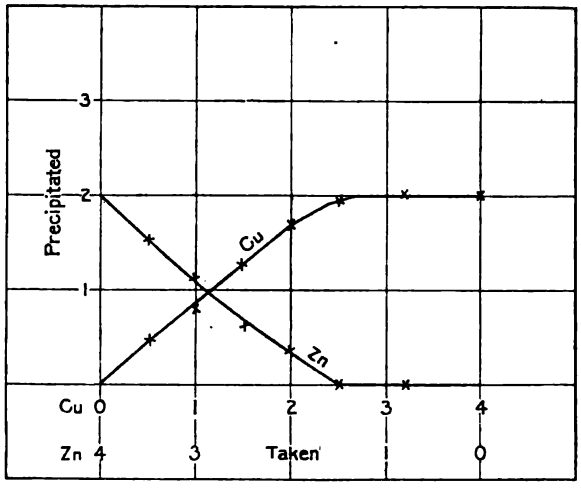

FIGURE 1.—Selective precipitation of copper before zinc by ammonium sulphide. The abscissæ represent the content of the solution in milligram equivalents of cupric sulphate and zinc sulphate before the addition of 2 milligram equivalents of ammonium sulphide; the ordinates represent the composition of the resulting precipitate.

alkaline solution more cupric sulphide is precipitated than zinc sulphide. The quantities of substances used are expressed in milligram equivalents. (See p. 12.) The solutions were dilute at the time of precipitation, the final volume being 40 cubic centimeters for the quantities stated in the table.

Fractional precipitation of cupric and zinc sulphates by ammonium sulphide.

[2.00 milligram equivalents in each precipitation.]

Cupric sulphate taken.	Zinc sulphate taken.	Copper in precipitate.	Zinc in precipitate.
Milligram equivalents.	*Milligram equivalents.*	*Milligram equivalents.*	*Milligram equivalents.*
0.00	4.00	0.00	2.00
.50	3.50	.49	1.51
1.00	3.00	.87	1.13
1.50	2.50	1.29	.60
2.00	2.00	1.70	.41
3.00	1.00	1.97	.02
3.20	.80	2.05	.00
4.00	.00	2.00	.00

These results are stated fully as illustrations of relations which hold for most pairs of sulphides. Both precipitate together at first, then one largely redissolves, leaving the sulphide radicle in combination with a single metal.

These facts may find application in theories of the formation of ores. If large bodies of precipitable solutions come into sudden contact, an indefinite mixture of sulphides will be precipitated. On the other hand, if the solutions are somewhat warm or react slowly the sulphides tend to be precipitated in a definite succession.

WORK OF ANTHON AND SCHÜRMANN.

The precipitation of soluble salts of metals by the insoluble sulphides of other metals was studied long ago by Anthon.[1] He obtained the series silver, copper, lead, cadmium, iron, nickel, cobalt, and manganese. A sulphide of any one of these metals, he found, would be precipitated at the expense of the sulphide of one lower in the series. The subject was studied further in 1888 by E. Schürmann,[2] who enlarged the series as follows: Palladium, mercury, silver, copper, bismuth, cadmium, antimony, tin, lead, zinc, nickel, cobalt, ferrous iron, arsenic, thallium, and manganese. The experiments of Anthon and Schürmann lead to exactly the same conclusions as those on fractional precipitation. The further investigation of sulphides was therefore restricted to some of the side issues involved. (See pp. 18–23.)

Schürmann found that some of these transpositions, of which he studied a very large number, occurred more easily than others, particularly those where the metals are widely separated in the series. It was especially difficult to obtain complete transformations in the case of nickel sulphide treated with zinc sulphate and between thallium salts and the neighboring members of the series. The

[1] Anthon, E. F., Jour. prakt. Chemie, vol. 10, p. 353, 1837.

[2] Schürmann, Ernst, Ueber die Verwandtschaft der Schwermetalle zum Schwefel: Liebig's Annalen, vol. 249, pp. 326–350, 1888.

behavior of iron was peculiar in that the sulphides of zinc, nickel, and cobalt formed at the expense of an excess of ferrous sulphide, but they were in turn dissolved when treated with ferrous sulphate. The positions of arsenic, tin, and antimony in the series are subject to qualifications depending on the valence of the metal.

This series for the order of solubility of sulphides has thrown great light on the development of sulphide ores.[1] It indicates the order of deposition of sulphides from a mixture of metallic salts when they compete under equal conditions for a sulphide. The first metals of the series will be precipitated first, leaving the solution richest in the last members; or, if solution is going on, the last members will tend, other things being equal, to go into solution first.

Schürmann was chiefly interested in determining the place of each metal in the series. He considered the series to represent the order of the "affinities" of the metals for sulphur. A more empirical statement is that it represents the order of the solubilities of the sulphides in water.[2]

If the mechanism of these reactions is considered according to present theories, we should have the following scheme of ionization in solution, for example, for the couple silver-copper:

$$\begin{array}{ccccc} Ag_2SO_4 & \rightleftharpoons & 2Ag^+ & + & SO_4^{=} \\ & & + & & + \\ CuS & \rightleftharpoons & S^{=} & + & Cu^{++} \\ & & \Downarrow & & \Downarrow \\ & & Ag_2S & & CuSO_4 \end{array}$$

Since the solubility product of silver sulphide is smaller than that of copper sulphide, silver sulphide forms at the expense of copper sulphide, and the equilibrium lies well toward the right in the following equation:

$$Ag_2SO_4 + CuS \rightleftharpoons Ag_2S + CuSO_4$$

The actual relations may be more complex than the last equation indicates, because there may also be a reaction of oxidation and reduction, but the scheme shows the general relation. Every sulphide has a "solubility product"; that is, the product of the concentrations of its two ions, which must be exceeded before precipitation can occur. Conversely, if the concentrations of the ions of any sulphide are less than its solubility product the sulphide will dissolve. That Schürmann's series is very nearly the order of solubility of the sulphides in pure water is evident from a comparison of the last column in the table on page 14 with Schürmann's series on page 16.

[1] Emmons, W. H., The enrichment of sulphide ores: U. S. Geol. Survey Bull. 529, p. 56, 1913.
[2] Wells, R. C., Econ. Geology, vol. 5, p. 7, 1910.

The idea of the solubility product allows us at once to explain certain facts noted by Schürmann and to predict others with reasonable confidence. For instance, it is not a matter of primary importance what acidic radicles are present in the solution as long as they do not form insoluble salts with the metals present. Again, the greater speed of adjustment of equilibrium for metals widely separated in the series accords with our present idea that the speed of reaction is a function of the remoteness of removal from equilibrium.

If we let K_1 and K_2 represent the solubility products of two sulphides involved in a fractional precipitation and write

$$K_1 = (M_1)\ (S)$$
$$K_2 = (M_2)\ (S)$$

where (M_1), (M_2) and (S) represent concentrations of metal 1, metal 2, and sulphide ions, then when equilibrium is established, since the sulphide ion is common, we should have

$$\frac{K_1}{K_2} = \frac{(M_1)}{(M_2)} \text{ or } \frac{(M_1)}{(M_2)} = K_3, \text{ a new constant.} \qquad (1)$$

That is, the ratio of the concentrations of the two metallic ions in a solution saturated with both sulphides should be a constant, independent of the quantity of sulphides but probably somewhat dependent on the temperature. Schürmann as a rule gave only qualitative results, and where he says one metal was "completely" separated from the other more exact research might show that a distribution occurs. As a matter of fact, however, the relation expressed by equation (1) above has not yet been experimentally illustrated in a quantitative way for sulphides.

A consideration of the solubility of sulphides helps to explain certain phenomena observed by Stokes.[1] He found that pyrite and marcasite are slightly attacked by a solution of alkali carbonate but much more completely when a carbonate of copper, lead, silver, or zinc is present. This is no doubt due in part to the greater insolubility of the sulphides of copper, lead, silver, or zinc, which form at the expense of the sulphide of iron in the pyrite and marcasite while the alkali dissolves the excess sulphur, the two concurrent reactions being much more effective than either singly.

COMPOUND SULPHIDES.

One of the objects in studying fractional precipitation was to gain light on the conditions of formation of compound sulphides, such as chalcopyrite. It is easy to perceive that the solubility of one sul-

[1] Stokes, H. N., Experiments on the action of various solutions on pyrite and marcasite: Econ. Geology vol. 2, p. 19, 1907.

phide might be changed by the presence of a second in solution and that a compound sulphide might have an intermediate solubility, following the usual behavior as described by Van't Hoff for double salts. The sulphides are so insoluble, however, that no adequate study of their behavior over a wide range of conditions has as yet been made.

Grout[1] has suggested that compound sulphides may have been produced in some instances by the admixture of alkaline and acid solutions. This seems very probable. Malfatti[2] has described certain complex sulphides of iron of the formula $RFeS_2$ where R is a univalent radicle. But in chalcopyrite copper has usually been regarded as bivalent, if the formula is written CuS.FeS; to write it $Cu_2S.Fe_2S_3$ suggests trivalent iron. However that may be, if chalcopyrite could be formed by a simple precipitative reaction its formation would remove the constituents from a solution in definite proportions. Such removal would modify curves like those shown in figure 1 (p. 15) into lines with horizontal sections over certain regions. As no such horizontal sections were discovered in the fractional precipitation of copper and iron sulphide the conditions for the formation of chalcopyrite were not revealed by that method.[3] It was therefore concluded that the formation of chalcopyrite by a precipitative reaction at moderate temperature and pressure demands at least more precipitating sulphide than corresponds to the copper present; otherwise no iron will be precipitated. Further investigation of this subject is needed.

By microscopic examination of the lean Butte ores J. F. Simpson has shown that the pyrite contains the copper as the copper minerals chalcocite, bornite, chalcopyrite, and enargite, and that of such minerals chalcopyrite is the oldest.[4] Graton and Murdock have reached similar conclusions after an examination of many specimens from other localities.[5] The typical minerals of enrichment processes appear to have been formed by the progressive alteration of one mineral into another, not strictly a fractional precipitation, although the fractionating tendency is revealed by the removal of the iron and the increasing deposition of copper. For the formation of the compound sulphides by enrichment the iron sulphide is already present. Of course, chalcopyrite may also result from magmatic differentiation, but for aqueous solutions we can not avoid the conclusion that its formation

[1] Grout, F. F., On the behavior of cold acid sulphate solutions of copper, silver, and gold with alkaline extracts of metallic sulphides: Econ. Geology, vol. 8, 1913.

[2] Malfatti, H., Beiträge zur Kenntnis des Eisensulfids: Zeitschr. anal. Chemie, vol. 48, p. 352, 1909.

[3] For details see Econ. Geology, vol. 5, p. 1, 1910.

[4] Simpson, J. F., The relation of copper to pyrite in the lean copper ores of Butte, Mont.: Econ. Geology, vol. 3, p. 635, 1908.

[5] Graton, L. C., and Murdock, Joseph, The sulphide ores of copper: Am. Inst. Min. Eng. Bull., May, 1913, pp. 741–812.

indicates the presence of an excess of available sulphide beyond the requirements of the copper. Briefly, a small amount of a soluble sulphide, say sodium sulphide, acting on a considerable quantity of ferrous and cupric sulphates does not produce chalcopyrite but only copper sulphide.

REDUCING ACTION OF SULPHIDES.

Besides taking part in purely metathetic reactions both soluble and insoluble sulphides may act as reducing agents. This action may be referred to the slight electroaffinity of sulphur, which produces the partial reaction:

$$S^{--} = S + 2\ominus$$

This reaction has a strong tendency to occur whenever it can be linked with a reaction of positive ions yielding positive electricity. For example, we are familiar with the action of hydrogen sulphide in acid solution on ferric salts:

$$2FeCl_3 + H_2S = 2FeCl_2 + S + 2HCl$$

If the reaction is considered to be essentially one between ions we have:

$$2Fe^{+++} + S^{--} = 2Fe^{++} + S \qquad (2)$$

This reaction shows the neutralization of the positive and negative charges and the precipitation of free sulphur.

The application of the reducing tendency of sulphide ions here suggested and illustrated should lead to interesting conclusions with other than iron salts. With cupric salts, for example, we should expect that the sulphide ions would tend to reduce cupric ions, along the line of the following equation:

$$2Cu^{++} + S^{--} = 2Cu^{+} + S \qquad (3)$$

Data on this possibility are scanty. Several investigators [1] have called attention to the fact that hydrogen sulphide produces in a solution of cupric sulphate a precipitate in which there is some free sulphur and a deficit in the amount of combined sulphur required by the formula CuS. According to Schweizer, there is usually about 7.2 per cent cuprous sulphide (Cu_2S)—that is, if the complex is interpreted as a mixture of cupric and cuprous sulphide—but, according to the more recent work of Clark, if such a precipitate is filtered off and digested for a long time with a solution of hydrogen sulphide

[1] Thomsen, Julius, Ueber die Zusammensetzung des auf nassem Wege gebildeten Schwefelkupfers: Deutsche Chem. Gesell. Ber., vol. 11, p. 2043, 1878. Ditte, A., Action du sulfure de cuivre sur le sulfure de potassium: Compt. Rend., vol. 98, p. 1429, 1884. Brauner, Bohuslav, Action of hydrogen sulphide on cupric salt solutions: Chem. News, vol. 74, p. 99, 1896. Schweizer, E., Diss., p. 34, Erlangen, 1908. Clark, J. D., A chemical study of the enrichment of copper sulphide ores: New Mexico Univ., Diss., p. 106, 1914.

in water the residue after removal of free sulphur contains about 71 per cent cuprous sulphide.

The study of the ionic reaction suggested by equation (3) as a possible equilibrium governed by the mass law is rendered difficult by the fact that sulphur and the two sulphides of copper are very insoluble. Of the different concentrations in equation (3) that of Cu^{++} will be determined by the solubility product of cupric sulphide and that of Cu^{+} by the solubility product of cuprous sulphide. The concentration of free sulphur may presumably be varied from zero to that of a saturated solution of sulphur. The concentration of sulphide ions, S^{--}, may be varied most widely, both by changes in total concentration and by the use of alkaline solutions in which the ionization of hydrogen sulphide is enormously increased. The use of an alkaline solution also serves to keep the concentration of free sulphur, S, below that of a solution saturated with sulphur on account of the formation of alkali polysulphide.

If we increase the concentration of the sulphide ions, S^{--}, there should be an increase in the cuprous ion concentration, Cu^{+}, if equation (3) is significant, and presumably more cuprous sulphide might then be precipitated.

A number of experiments were made, directed wholly toward securing a precipitate with a high percentage of cuprous sulphide, especially by the use of alkaline solutions. The results are summarized in the following table. The precipitations were made hot by adding the cupric sulphate to the alkaline sulphide. The precipitate was washed by decantation, finally with alcohol and ether, well pressed between filter papers, and dried over sulphuric acid.

Action of alkaline soluble sulphide solutions on cupric sulphate.

Experiment.	Gram equivalents taken per liter of the mixture.			Percentage of Cu_2S in precipitate.
	$CuSO_4$.	Na_2S.	NaOH.	
126	0.091	0.091	0.017	18.3
127	.059	.112	.022	31.1
128	.035	.069	.130	47.6
130	.001	.002	.200	55.8
131	.016	.155	.146	61.8
129	.014	.028	.158	69.3
	$CuCl_2$			
132	.05	.10	.10	49.8

These results prove that the immediate precipitate produced by alkaline sulphides contains a much higher percentage of cuprous sulphide than that formed by hydrogen sulphide in acid solutions. The results strengthen the supposition that the equilibrium shown in equation (3) determines the composition of the precipitate to some

extent, since the sulphide ion concentration varies with the alkalinity.[1] It appeared impossible, however, by this method to obtain a precipitate of pure cuprous sulphide. The experiments of Ditte show that a concentrated solution of potassium sulphide will convert copper entirely into the cuprous state, but he says that a dilute solution is without effect.[2] My experiments seem to modify Ditte's conclusions. The further solution of the problem would seem to require a more careful study of the reversibility of the action with respect to variations in the concentrations of sulphide ions and free sulphur.

The reducing action of sulphide ions on other metallic salt solutions has not been studied.

ELECTRIC ACTIVITY IN SULPHIDES.

Since insoluble metallic sulphides are conductors of electricity the equalization of chemical differences, especially differences in degree of oxidation, can take place through electric action over appreciable distances. Thus the deposition of such metals as gold, silver, and copper may occur at one end of a conducting filament while the oxidation of a sulphide or any other oxidizable substance is occurring at the other end of the system constituting the metallic portion of the circuit. The associations of products produced in this way will naturally be different from those produced under conditions of thorough admixture. Further, not only will dissimilar sulphides and metals manifest reciprocal influences on each other through electric activity but effects from active solutions will be transmitted as far as the complete circuits extend. I have discussed these matters in detail elsewhere[3] and need refer to only one phase of the subject further in this connection.

In studying chalcocite enrichment A. C. Spencer has reached the conclusion that the change of pyrite or chalcopyrite to chalcocite may be considered as an alteration involving a series of steps, or perhaps even a continuous progression through indefinite compounds or mixtures of iron-copper sulphides. He succeeded in bringing about the change of chalcopyrite at least into chalcocite through bornite and covellite in several artificial ways. One of these ways consisted in touching the specimens immersed in cupric sulphate by an iron nail. Since there is every reason to believe that the iron affected the sulphides through electric action it seems worth while to quote his account of this experiment as an illustration of possible electric action.[4]

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[1] Knox, Joseph, A study of the sulphur anion and of complex sulphur anions: Faraday Soc. Trans., vol. 4, p. 47, 1908.

[2] Ditte, A., Compt. Rend., vol. 98, p. 1429, 1884.

[3] Wells, R. C., Electric activity in ore deposits: U. S. Geol. Survey Bull. 548, 1914.

[4] Spencer, A. C., Chalcocite enrichment: Econ. Geology, vol. 8, p. 629, 1913.

The colors * * * referred to above may be readily obtained by another simple procedure, and the observer can hardly fail to conclude that the colors obtained indicate the formation of the minerals bornite, covellite, and chalcocite. If any member of the series chalcopyrite, bornite, covellite is touched by a piece of iron while it is immersed in a cupric sulphate solution the mineral changes color almost instantly and in a short time becomes coated with the mineral next above it in the series. The brilliant indigo of covellite changes to the dull gray so characteristic of chalcocite, bornite assumes a blue color unmistakably like that of covellite, and chalcopyrite takes on a bronzy hue resembling that of bornite. Furthermore, within a very short time the bronze plating on chalcopyrite gives place to or is hidden by a film of covellite; then within an hour or so the surface turns to a chalcocite gray, and finally metallic copper is deposited. When pyrite is used in place of a cupriferous sulphide the effect of the iron is sufficient to throw down metallic copper rather quickly, but by scraping away the metal and again placing the mineral in contact with iron in the solution it is possible to obtain deposits of copper sulphides. In this way spots having somewhat the same color as chalcopyrite and others bronzy like bornite may be developed on pyrite along with unmistakable films of covellite and of chalcocite. If copper is used instead of iron the results are essentially the same with chalcopyrite, bornite, and covellite. For instance, covellite may be coated with chalcocite by contact with copper in a solution of cupric sulphate. It is obvious that the speed of reaction may be varied by employing different metals as inductors, or by employing minerals to cause electrolytic action. Very pleasing results have been obtained by placing in a solution of cupric sulphate a polished specimen of intergrown chalcopyrite and pyrrhotite. Here a pinkish bronze color resembling that of bornite appeared within a few days, but gradually changed to purple, deep purple, and finally to indigo blue. On the most reactive grains the covellite color was fully developed in about eight weeks, but the surface in general became blue only after 12 weeks, and even then certain areas were still bronzy. At the end of four months no gray color had developed to indicate the formation of chalcocite, but the color was a paler blue than that of natural covellite.

It may be suggested that the results described, which were obtained under ordinary temperatures, may actually epitomize the course of reaction between the primary sulphides and copper salts held in oxidized solutions penetrating from the surface. Even if the means employed to produce the results in a short time are not comparable with those involved in natural processes, perhaps the conditions under which the experiments were made may be considered to be less unnatural than those prevailing in mineral syntheses effected under high temperatures.

SUMMARY OF RESULTS OF EXPERIMENTS WITH SULPHIDES.

1. The concentration of the sulphide ion is so greatly affected by change of acidity that this change is the principal factor determining the precipitation of sulphides.

2. The solubility of the several sulphides, however, differs so greatly that complete separations by fractional precipitation are possible; for example, copper from zinc.

3. A mixture of two metallic salts yields, by fractional precipitation, an initial precipitate containing the sulphides of both metals, but as a rule, if the mixture is heated or is permitted to stand, one sulphide largely or wholly redissolves.

4. The order of precipitation, beginning with the metal that separates first, is palladium, mercury, silver, copper, bismuth,

cadmium, antimony, tin, lead, zinc, nickel, cobalt, ferrous iron, arsenic, thallium, manganese.

5. Attempts to form chalcopyrite by fractional precipitation of ferrous and cupric sulphate were unsuccessful.

6. Soluble sulphides may act as reducing agents. This action affects the composition of precipitates of copper sulphide and may explain the anomalous position of silver in the precipitation series.

7. At one stage of the action produced by an admixture of sulphides and metallic salts electric activity may determine the products formed.

HYDROXIDES.

PREVIOUS WORK.

Only a few experiments are found in the literature on the fractional precipitation of the common metallic hydroxides. Mills and Smith,[1] in working on nickel and cobalt, found a very narrow margin of difference in precipitability, but this is probably one of the most difficult pairs to separate, although my own experiments indicate that manganese and magnesium are similarly close together. Fink[2] obtained the precipitation series copper, zinc, nickel, cobalt, manganese, and magnesium for the hydroxides of these metals. Pickering[3] studied the partial precipitation of copper sulphate solutions only by calcium hydroxide, but this was not strictly a fractionation.

SOLUBILITY OF HYDROXIDES.

The preliminary data available in regard to the solubility of the hydroxides at room temperatures of 20°–25° C., are as follows:

Solubility of hydroxides.

	Gram equivalents per liter.
$Zn(OH)_2$	6.0×10^{-6}
$Cd(OH)_2$	8.7×10^{-6}
$Mn(OH)_2$	3.0×10^{-5}
Ag_2O	4.6×10^{-5}
$Pb(OH)_2$	9.3×10^{-5}
$Fe(OH)_2$ (Lamb[4])	2.7×10^{-5}
$Mg(OH)_2$	7.5×10^{-4}
HgO	2.5×10^{-4}
$Ca(OH)_2$	4.5×10^{-2}
$Sr(OH)_2$	1.3×10^{-1}
$Ba(OH)_2$	4.6×10^{-1}

[1] Mills, E. J., and Smith, J. J., Researches in chemical equivalence: Roy. Soc. Proc., 5th ser., vol. 29, p. 181, 1879.

[2] Fink, R., Ueber die Affinität der Vitriolmetalle zur Schwefelsäure: Deutsche chem. Gesell. Ber., vol. 20, p. 2106, 1887.

[3] Pickering, S. U., The chemistry of Bordeaux mixture: Chem. Soc. Trans., vol. 91, p. 1989, 1907; vol. 97, p. 1852, 1910.

[4] Lamb, A. B., The potential of iron calculated from equilibria measurements: Am. Chem. Soc. Jour., vol. 32, p. 1218, 1910.

FRACTIONAL PRECIPITATION OF HYDROXIDES.

By the procedure used in the study of the sulphides the hydroxides of the important metals were fractionally precipitated as follows: To a dilute solution containing two metallic salts in equivalent quantity, heated nearly to boiling, was added a dilute solution of sodium hydroxide sufficient to precipitate one metal only. The sodium hydroxide contained some barium hydroxide, used to free it from carbonate. Oxidizable salts were precipitated in an atmosphere of hydrogen. The precipitate was kept at a temperature close to 100° for several minutes and finally filtered off. An aliquot portion of the filtrate was analyzed and the composition of the precipitate was thus determined. In general one metal was precipitated to a greater extent than the other, and after working out a number of pairs it was found possible to arrange the metals in a series, which may be termed the hydroxide precipitation series. Although in the experiments with the sulphides the proportions in the precipitate were determined, in nearly every experiment with the hydroxides the results were limited at first to the determination of the order in the series. This order was found to be as follows:

Order of solubility of hydroxides.

1. Ferric hydroxide.
2. Aluminum hydroxide.
3. Cupric hydroxide.
4. Zinc hydroxide.
5. Lead hydroxide.
6. Nickelous hydroxide.
7. Silver hydroxide.
8. Ferrous hydroxide.
9. Manganous hydroxide.
10. Magnesium hydroxide.
11. Calcium hydroxide.

The pairs determined are shown in the next table.

Pairs of metals compared in fractional precipitation of hydroxides.

Experiment.	Major constituent of precipitate.	Minor constituent of precipitate.
113	Ferric hydroxide	Aluminum.
111	do	Copper.
112	Aluminum	Do.
97	Copper	Zinc.
98	do	Lead.
109	do	Nickel.
112	do	Ferrous hydroxide.
96	do	Magnesium.
100	Zinc	Lead.
10	do	Nickel.
102	do	Ferrous hydroxide.
99	Lead	Silver.
	do	Magnesium.
106	Nickel	Silver.
	do	Ferrous hydroxide.
101	Silver	Magnesium.
103	Ferrous hydroxide	Do.
105	do	Do.
109	Manganese	Calcium.
110	Magnesium	Do.

It will be seen that the precipitation series does not follow the solubility series very closely. Possibly some of the solubility determinations are incorrect, or the matter of hydrolysis may not have been sufficiently considered. However that may be, it is significant

that the precipitation series may be correlated with a heat effect, namely with the heat of the reaction

Sodium hydroxide+metallic sulphate=metallic hydroxide+sodium sulphate.

These heats of reaction are shown in the table below.

Order obtained for the heat of reaction of sodium hydroxide with metallic sulphates.

M	1	2	M	1	2
Hg^{++}	.....	11.78	Pb	.....	4.79
Hg^{+}	.....	10.57	Zn	3.99	3.77
Fe^{+++}	10.05	.....	Cd	3.59	3.56
Ag	.....	8.24	Co	3.35	3.13
Cr	7.47	.....	Fe^{++}	3.23	3.01
Cu	6.47	6.25	Ni	2.64	2.42
Al	5.19	.....	Mn	2.45	2.23

1. $NaOHaq+M(SO_4)_{1/2}aq=Na(SO_4)_{1/2}aq+MOH$.
2. $NaOHaq+MNO_3aq=NaNO_3aq+MOH$.

Although the order here shown does not yet agree exactly with the order obtained in the fractional precipitations the agreement is closer than that between the precipitation series and the order of the solubilities determined directly (p. 24).

FERROUS AND CUPRIC HYDROXIDES.

For the purpose of studying one fractionation in greater detail the precipitation of iron and cupric hydroxides was studied over a wide

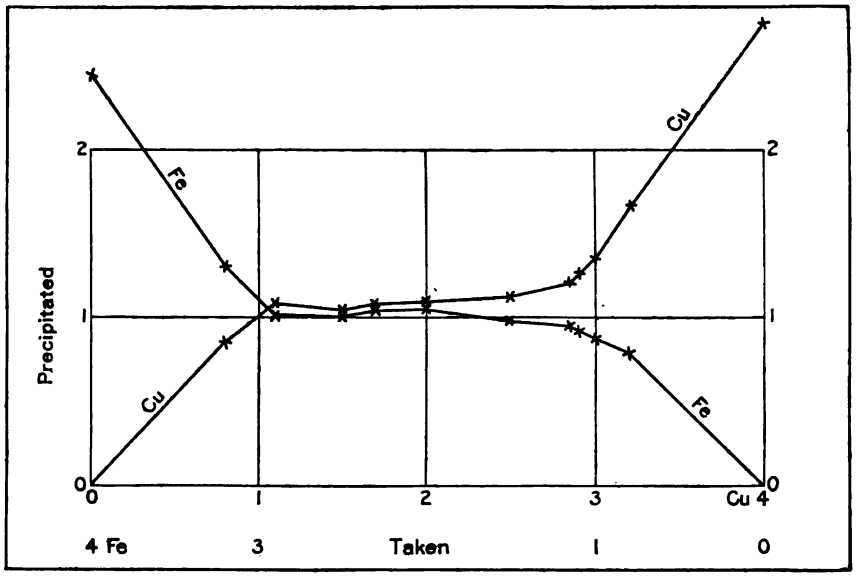

FIGURE 2.—Apparent selective precipitation with ferrous and cupric sulphates. The abscissæ represent the content of the solution in milligram equivalents of ferrous and cupric sulphate before the addition of 2 milligram equivalents of ammonium hydroxide, the ordinates the composition of the resulting precipitate.

range of concentrations. The fractionations in the table below were carried out with ammonium hydroxide as the precipitant. The results are also plotted in figure 2. Dilute solutions were used for

these precipitations, the final volume in every experiment being 40 cubic centimeters for the quantities stated in the table.

Precipitation of ferrous and cupric sulphate by ammonium hydroxide (milligram equivalents).

Cupric sulphate taken.	Ferrous sulphate taken.	Copper in precipitate.	Iron in precipitate.	Color of precipitate.
0.00	4.00	0.00	2.43	Pale green.
.80	3.20	.80	1.30	Black.
1.10	2.90	1.08	1.01	Do.
1.50	2.50	1.03	1.01	
1.70	2.30	1.08	1.05	Brownish.
2.00	2.00	1.09	1.07	
2.50	1.50	1.12	.97	
2.85	1.15	1.20	.95	Orange.
2.90	1.10	1.26	.91	Do.
3.00	1.00	1.33	.87	Do.
3.20	.80	1.66	.68	
4.00	.00	2.75	.00	Green.

These results show a very peculiar selective precipitation. At the extreme concentrations basic salts are precipitated. Although it seemed at first as if the results indicated the formation of a precipitate containing one atom of iron to one of copper, it was afterward concluded that the oxidation of the ferrous salt had not been wholly prevented, and in fact that it could not be wholly prevented on account of the presence of cupric sulphate. As a result of this oxidation ferric hydroxide was precipitated instead of ferrous hydroxide, and therefore the assumption of the formation of a complex compound is unwarranted.

Similarly solutions of cupric sulphate and ferrous sulphate in varying proportions were precipitated hot out of access of air by sodium hydroxide.

Precipitation of ferrous and cupric sulphate by sodium hydroxide (milligram equivalents).

Ferrous sulphate taken in 250 cubic centimeters.	Cupric sulphate taken in 250 cubic centimeters.	Iron precipitated by 4 milligram equivalents of sodium hydroxide.	Copper precipitated.
1.50	6.50	1.15	.....
4.00	4.00	1.78	.....
6.20	1.80	2.03	1.79

These results show that the copper has a greater tendency to precipitate where equal amounts of both salts are present, and this tendency causes the practical removal of the copper where it is the minor constituent. What looks like evidences of the formation of a molecule $FeCu(OH)_4$ may again be due simply to unpreventable oxidation of a portion of the ferrous salt.

Recently Curtman and St. John[1] have studied the sensitiveness of the hydroxide reactions for the common metals. They find an order of sensitiveness which differs considerably from the precipitation series here deduced, but it appears that their results are based on optical effects, such as the visibility, color, and density of the precipitates, so that an exact agreement is not to be expected.

SUMMARY OF RESULTS OF EXPERIMENTS WITH HYDROXIDES.

1. The precipitation series obtained for the hydroxides, beginning with the most insoluble compound, is as follows: Ferric hydroxide, aluminum, cupric hydroxide, zinc, lead, nickel, silver, ferrous hydroxide, manganous hydroxide, magnesium, calcium.

2. The series is very nearly the same as that for the heat required for the formation of the hydroxides, namely: Mercury, ferric hydroxide, silver, copper, aluminum, lead, zinc, cadmium, cobalt, ferrous hydroxide, nickel, manganese.

3. When cupric and ferrous salts are precipitated together by a soluble hydroxide the iron tends to appear as ferric hydroxide, and this fact explains the apparent exceptional precipitation of the two metals together as hydroxides in spite of the fact that cupric hydroxide is more insoluble than ferrous hydroxide.

CARBONATES.

PREVIOUS WORK.

In 1853 Debus[2] published some quantitative experiments on the fractional precipitation of barium and calcium carbonate. Although some of his conclusions are faulty, an examination of his results shows that calcium competing with barium is precipitated to a greater extent than barium by a soluble carbonate. No other experiments on the fractional precipitation of carbonates have come to my attention except those reported in 1882 by Mills and Bicket[3] on the fractional precipitation of nickel and manganous sulphates and nickel and cadmium sulphates by a slight deficiency of sodium carbonate. Their experiments clearly show that cadmium is precipitated to a greater extent than nickel and that nickel is precipitated to a greater extent than manganese under equal terms of competition. Their experiments were made in the cold and no time was allowed for any possible readjustment. Other experiments by them on the separate precipitability of these salts show that rather complex precipitates are obtained.

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[1] Curtman, L. J., and St. John, A. D., Am. Chem. Soc. Jour., vol. 34, p. 1679, 1912.

[2] Debus, H., Ueber chemische Verwandtschaft: Liebig's Annalen, vol. 85, p. 124, 1853.

[3] Mills, E. J., and Bicket, J. H., Researches on chemical equivalence: Philos. Mag., 5th ser., vol. 13, pp. 169, 177, 1882.

T. Sterry Hunt[1] states that a gypsum solution loses no calcium to crystalline dolomite or crystalline carbonate of magnesium; and that even in the presence of carbon dioxide very little magnesium is taken into solution; but with hydrated magnesium carbonate or hydrate of magnesium there is considerably more magnesium dissolved.

To determine the behavior of certain heavy metals with an excess of carbon dioxide at ordinary temperatures Raikow studied the action of that gas on their hydroxides.[2] He found that basic carbonates were formed with glucinum and yttrium, that acid carbonates were formed with magnesium, thallium, nickel, and cobalt and slightly with manganese and ferrous iron, and that all the other carbonates were normal. His results do not include any statement of the solubility or insolubility of the carbonates so formed, although they indicate that with an excess of carbon dioxide only silver, cadmium, mercurous, lead, and copper salts among the common elements form insoluble precipitates to any great degree of completeness.

SOLUBILITY OF CARBONATES.

The preliminary data available in regard to the solubility of the carbonates are as follows:

Solubility of carbonates in pure water.

	Temperature.	Gram equivalents per liter.	Authority.
	°C.		
$PbCO_3$	18	1.6×10^{-6}	M. Pleissner.[a]
$FeCO_3$	15	6.2×10^{-6}	J. von Essen.[b]
$ZnCO_3$	15	1.7×10^{-4}	Do.
$BaCO_3$	16	1.9×10^{-4}	
$CaCO_3$ (calcite)	16	2.6×10^{-4}	T. Schloesing.[c]
$CaCO_3$ (aragonite)	15	3.4×10^{-4}	J. von Essen.[b]
	25	2.86×10^{-4}	J. Kendall.[d]
	100	3.56×10^{-4}	Do.
	15	3.0×10^{-4}	R. Abegg.[e]
	25	3.06×10^{-4}	J. Kendall.[d]
	100	3.80×10^{-4}	Do.
$SrCO_3$	15	3.2×10^{-4}	J. von Essen.[b]
$CoCO_3$	15	4.4×10^{-4}	Do.
$MnCO_3$	15	4.6×10^{-4}	Do.
$NiCO_3$	15	4.7×10^{-4}	Do.
$MgCO_3$	15	2.4×10^{-3}	Do.
Tl_2CO_3	15	1.7×10^{-1}	
Li_2CO_3	15	3.7×10^{-1}	
Na_2CO_3	15	2.6	

[a] Ueber die Löslichkeit einiger Bleiverbindungen in Wasser: Arbeiten aus dem Kaiserl. Gesundheitsamt, Bd. 26, Heft 3, Berlin (Julius Springer), 1907.
[b] Recherches expérimentales sur la solubilité des carbonates et des bicarbonates, Thesis, Geneva, 1897.
[c] Compt. Rend., vol. 74, p. 1555, 1872.
[d] Philos. Mag., vol. 23, p. 958, 1912.
[e] Abegg, R., Handbuch der anorganischen Chemie, Bd. 2, Abt. 2, p. 157, 1905.

The uncertainty of some of these data is illustrated by the figures for silver carbonate, which does not appear in the table. Cox[3]

[1] Chemical and geological essays, p. 107, 1878.
[2] Raikow, P. W., Weitere Untersuchungen über die Einwirkung der Kohlensäure auf die Hydrate der Metalle: Chem. Zeitung, vol. 31, p. 55, 1907.
[3] Cox, A. J., Ueber die Löslichkeitsverhältnisse einiger schwerlöslicher Silbersalze: Zeitschr. physikal. Chemie, vol. 46, p. 11, 1903.

gives 17 parts per million, whereas Moissan[1] gives 30 at 15° C. Moissan states that this is increased to 1,040 parts per million when the water is saturated with carbon dioxide. Discrepancies in many of the determinations are probably due to the fact that the acidity of the solutions was not exactly controlled. Even the slight amount of carbon dioxide in the air increases the solubility of carbonates enormously.

EFFECT OF HYDROLYSIS.

Owing to hydrolysis hydroxides, not carbonates, are precipitated with aluminum, ferric, and chromic salts. "Basic carbonates" are precipitated under ordinary circumstances with zinc, nickel, cobalt, copper, and mercuric salts, and boiling removes the carbon dioxide from these salts to a greater or less extent. When hydrolysis is not so pronounced or the hydroxide is more soluble, normal carbonates are formed as with calcium, manganese, ferrous iron, cadmium, silver, lead, and mercurous salts; these are unchanged on boiling, but the carbonates of lead, mercury, and silver are changed to basic carbonates in time. Lead carbonate suspensions become alkaline at 70° according to Abegg.

For carbonates the chief hydrolytic reaction would be

$$CO_3^{--} + HOH = HCO_3^- + OH^-$$

and to a less extent

$$HCO_3^- + HOH = H_2CO_3 + OH^-$$

The degree of hydrolysis of sodium carbonate at 24.1° is shown below for the concentrations stated, the degree expressing the percentage of total sodium present in the form of the hydroxide.

Hydrolysis of sodium carbonate at 24.1° C.

Moles Na_2CO_3 per liter	0.1900	0.0940	0.0477	0.0238
Per cent hydrolysis	2.12	3.17	4.87	[2] 7.10

The hydrolysis of sodium carbonate may be increased by boiling the solution and the removal of carbon dioxide as follows, starting with a normal solution:[3]

Hydrolysis of sodium carbonate produced by boiling.

Time of boiling (hours)	1.25	3.5	6.0	8.5	23.3	38.0
Remaining Na_2CO_3 (per cent)	96.7	94.6	92.7	91.4	87.0	83.8
NaOH formed (per cent)	3.3	5.4	7.3	8.6	13.0	17.2

[1] Moissan, H., Traité de chimie minérale, vol. 5, p. 590, 1904–1906.

[2] Shields, John, Ueber Hydrolyse in wässerigen Salzlösungen: Zeitschr. physikal. Chemie, vol. 12, p. 167, 1893.

[3] Küster, F. W., and Grüters, Max, Ueber den Zerfall von gelöster Soda in Kohlendioxyd und Natriumhydroxyd: Deutsche chem. Gesell. Ber., vol. 36, p. 748, 1903.

EXPERIMENTS WITH CARBONATES AT ORDINARY TEMPERATURE.

In making fractional precipitations of carbonates two metallic salts were precipitated by less than their chemical equivalent of soluble carbonate and the ratio of the metals in the precipitate determined.

The first precipitations were made in flasks which stood at the temperature of the laboratory and were shaken from time to time. The analyses were carried out by difference—that is, by analyzing an aliquot part of the solution after filtering off the precipitates and subtracting the quantities found from the quantities taken. The general scheme of this ionization and reaction in solution may be illustrated by a mixture of zinc sulphate, calcium sulphate, and sodium carbonate, as follows:

$$\begin{array}{ccccc} (Zn,Ca)SO_4 & = & (Zn,Ca)^{++} & + & SO_4^{--} \\ & & + & & + \\ Na_2CO_3 & = & CO_3^{--} & + & 2Na^+ \\ & & \| & & \| \\ & & (Zn,Ca)CO_3 & & Na_2SO_4 \end{array} \qquad (4)$$

Since, in the fairly dilute solutions used, the soluble salt, in this experiment sodium sulphate, plays an insignificant part, the scheme may be simplified even further, as follows:

$$(Zn,Ca)^{++} + CO_3^{--} = (Zn,Ca)CO_3 \qquad (5)$$

Information can be gained in the first place by considering what will happen when equivalent quantities of the two metals are present, with just enough carbonate for one, and afterward by noting whether the result so found is changed for other proportions of the metals.

From equation (5) it is evident that the equilibrium to be determined may be obtained by precipitating both the metallic salts with a soluble carbonate or by treating a carbonate of one metal with a soluble salt of the other metal. The first method was chiefly used, and the results are presented below.

In these results the radicles and metals are expressed in milligram equivalents, an equivalent being equal in milligrams to the molecular weight of the metal or radicle reduced to a univalent basis. The solution was made up to 1 liter in every experiment, or was calculated to that basis.

Preliminary results of experiments with carbonates at 25° C., with equivalent quantities of two metals present and carbonate enough for one.

Quantity taken (milligram equivalents).		Quantity precipitated (milligram equivalents).	
Experiment 4.			
$ZnSO_4$	8.0	Zinc	6.52
$CaSO_4$	8.0	Calcium	None.
Na_2CO_3	8.0		
Time, 17 days.			
Experiment 5.			
$CdSO_4$	20.0	Cadmium	15.5
$ZnSO_4$	20.0	Zinc	4.5
Na_2CO_3	20.0		
Time, 19 days.			
Experiment 6.			
$FeSO_4$	10.0	Iron	6.25
$CaSO_4$	10.0	Calcium	None.
Na_2CO_3	10.0		
Time, 3 days.			
Experiment 7.			
$CuSO_4$	10.0	Copper	5.30
$FeSO_4$	10.0	Iron	5.35
Na_2CO_3	10.0		
Time, 2 days.			
Experiment 8.			
$CuSO_4$	8.0	Copper	6.84
$ZnSO_4$	8.0	Zinc	.76
Na_2CO_3	8.0		
Time, 26 days.			

Prescott and Johnson[1] state that calcium carbonate has no action on zinc salts at ordinary temperature. Since the above experiment shows a considerable precipitation of the zinc—to be exact, 6.52 milligram equivalents in 8 or 81.5 per cent in 17 days—it appears that the duration of the experiment is a factor to be considered. This was confirmed by further experiments, in which finely powdered calcite was introduced into zinc sulphate instead of precipitating the two salts with sodium carbonate.

In one experiment (No. 12) 8 milligram equivalents of calcite were introduced into 8 milligram equivalents of zinc sulphate in a liter. The flask was shaken occasionally at room temperature. After 2 days 16.5 per cent of the zinc was precipitated, and after 24 days 81.2 per cent was precipitated.

In another experiment (No. 9) precipitated calcium carbonate, which had been previously dried and heated, was digested at 20°–25° for 3 hours with dilute zinc sulphate. No zinc was precipitated.

[1] Prescott, A. B., and Johnson, O. C., Qualitative chemical analysis, 5th ed., p. 179, 1903.

These results show that hasty chemical experiments may lead to greatly mistaken conclusions in geologic investigations. At ordinary temperature several days are required to show the effect; and, in fact, it is not certain that equilibrium was attained in these experiments, but it is certain that calcium carbonate will precipitate considerable zinc in time, even at ordinary temperatures. On the other hand, too long continuation of experiments in glass vessels introduces an uncertainty on account of the slow production of basic salts due to the action of the glass.

The fact that in the first experiment with zinc sodium carbonate was added, whereas in those just mentioned calcite was used, necessitates a consideration of the varieties of calcium carbonate. It is generally true that a freshly precipitated substance is more soluble than the same substance after the lapse of time. With some substances this is due to the size of the particles, with others to the crystalline form, and these facts must be considered in precipitations with solids. As regards calcium carbonate, W. Meigen[1] has shown that when calcium chloride solutions are precipitated by sodium carbonate aragonite separates, in globules at low temperatures, in needles at high temperatures, and that on standing under some conditions this aragonite passes into calcite. Since aragonite is more soluble than calcite, it would be expected to have a slightly greater precipitating power on solutions of metallic salts than calcite. Meigen has shown that this is the case. This study has been continued by his students.[2]

Similar conclusions can be drawn from my own experiments with freshly precipitated calcium carbonate. As a variation of the fractionation in one experiment (No. 13), the calcium sulphate was first precipitated with its equivalent of sodium carbonate, then, without filtration, zinc sulphate was added, and in 2 hours 17.6 per cent of the zinc was precipitated. With the calcium carbonate which had been previously dried and heated no zinc was apparently precipitated, even in 3 hours, but after 24 days the zinc was practically all precipitated.

The conclusion from all the experiments with zinc and calcium at ordinary temperature is that calcium carbonate in any form will ultimately precipitate a considerable amount of zinc from zinc sulphate solutions but that the metathesis takes time to occur. Moreover, it occurs slowly with well-dried calcium carbonate, more quickly with aragonite than with calcite, and most quickly with freshly precipitated calcium carbonate.

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[1] Naturf. Gesell. Freiburg im Breisgau Ber., Bd. 30, p. 64, 1903.

[2] Gassner, L., Weitere Beiträge zur Kenntniss des kohlensauren Kalks: Inaug. Diss., Freiburg im Breisgau, 1906.

These results immediately suggest new experiments concerning the action of calcium carbonate on salts of iron, aluminum, chromium, cobalt, nickel, and manganese. It is held in qualitative analysis that a suspension of freshly precipitated calcium carbonate will precipitate ferric, aluminum, and chromic salts in the cold, but have no action on ferrous, cobalt, nickel, manganese, and zinc salts. Chromic salts are said to precipitate more slowly than aluminum or ferric salts.[1]

According to Meigen's researches,[2] a hundredfold excess of calcite precipitated a 0.045 normal solution of manganese to the extent of 2.9 per cent in 72 hours at 17°, and aragonite precipitated 70.2 per cent under the same conditions.

In experiment 21 calcite was tried with nickel sulphate; 5.10 milligram equivalents of nickel sulphate and 4 milligram equivalents of sodium sulphate in 500 cubic centimeters of water were shaken occasionally with 4 milligram equivalents of powdered calcite for 17 days. The precipitate then showed 0.36 milligram equivalents of nickel and 3.89 milligram equivalents of calcium. Hence the precipitation of the nickel by calcite after 17 days was slight, only about 7 per cent of the whole quantity, but experiment 87 shows that time is an important factor in this action and that eventually nickel is very largely if not completely precipitated.

Magnesium carbonate, like calcium carbonate, is known to exist in several forms which differ in solubility and which must therefore also differ in their capacity for precipitating other carbonates. The most soluble form is the trihydrate, $MgCO_3.3H_2O$. A liter of pure water saturated with this salt contains 0.23 gram of magnesium and 0.42 gram carbon dioxide at 20°, according to Auerbach,[3] in the absence of any excess of carbon dioxide. I have found its solubility under atmospheric conditions, that is, its solubility in water in equilibrium with air containing the normal amount of carbon dioxide, to be somewhat greater, namely, 0.36 gram magnesium per liter, total carbon dioxide 1.01 gram per liter. Amorphous magnesite was found to be much less soluble than this. No experiments were made with crystallized magnesite, which is rather difficult to obtain.

Other fractional experiments were made, beginning with experiment 22, the results of which, together with the preceding experiments, are shown in the following table, all results corresponding to a volume of 1 liter. In most experiments 8 milligram equivalents of sodium carbonate were used, but a few variations were made, as follows: Experiment 32, 10.28; experiment 34, 8.80; experiment 39, 8.30; experiments 71 and 74, 16 milligram equivalents of sodium carbonate.

[1] Prescott, A. B., and Johnson, O. C., Qualitative chemical analysis, 5th ed., p. 154, 1903.
[2] Op. cit., p. 83.
[3] Auerbach, F., Zeitschr. Elektrochemie, vol. 10, p. 161, 1904.

Summary of fractional precipitations of carbonates at ordinary temperature.

Experiment.	Quantity of mixture taken (milligram equivalents per liter).		Duration of experiment (days).	Quantity of the metal found in precipitate (milligram equivalents).	
4	8 $ZnSO_4$	8 $CaSO_4$	17	6.52 zinc	Tr. calcium.
5	20 $CdSO_4$	20 $ZnSO_4$	19	15.5 cadmium	4.5 zinc.
6	10 $FeSO_4$	10 $CaSO_4$	3	6.25 iron	Tr. calcium.
7	10 $CuSO_4$	10 $FeSO_4$	2	5.30 copper	5.35 iron.
8	8 $CuSO_4$	8 $ZnSO_4$	26	6.84 copper	0.76 zinc.
22	8 $Pb(NO_3)_2$	8 $AgNO_3$	4	8.00 lead	0.08 silver.
23	8 $Pb(NO_3)_2$	8 $Cd(NO_3)_2$	6	8.00 lead	0.42 cadmium.
24	8 $Zn(NO_3)_2$	8 $Pb(NO_3)_2$	6	7.96 lead	Tr. zinc.
25	8 $AgNO_3$	8 $HgNO_3$	24	2.28 silver	7.98 mercury.
26	8 $AgNO_3$	8 $Cd(NO_3)_2$	4	0.30 silver	7.18 cadmium.
27	8 $ZnSO_4$	8 $NiSO_4$	10	5.00 zinc	1.50 nickel.
28	8 $AgNO_3$	8 $Zn(NO_3)_2$	8	1.60 silver	3.96 zinc.
29	8 $FeSO_4$	8 $NiSO_4$	1	4.20 iron	3.06 nickel.
30	8 $FeSO_4$	8 $Zn(NO_3)_2$	1	2.66 iron	2.64 zinc.
31	8 $Cd(NO_3)_2$	8 $HgNO_3$	11	3.54 cadmium	7.36 mercury.
32	8 $MnSO_4$	8 $CaSO_4$	2	6.56 manganese	1.64 calcium.
33	8 $NiSO_4$	14.54 $MgSO_4$	5	5.94 nickel	Tr. magnesium.
34	8 $NiSO_4$	8 $MnSO_4$	9	4.04 nickel	3.80 manganese.
39	8 $AgNO_3$	8 $MnSO_4$	7	3.98 nickel	5.76 manganese.
41	8 $AgNO_3$	8 $CaSO_4$	7	6.80 silver	1.56 calcium.
42	8 $CaSO_4$	8 $MgSO_4$	8	1.60 calcium	1.12 magnesium.
55	8 $HgNO_3$	8 $Pb(NO_3)_2$	6	3.50 mercury	0.75 lead.
60	8 $CuSO_4$	8 $CdSO_4$	8	7.24 copper	0.20 cadmium.
64	8 $NiSO_4$	8 $AgNO_3$	6	3.16 nickel	2.96 silver.
71	16 $ZnSO_4$	16 $MnSO_4$	(a)	11.96 zinc	8.96 manganese.
74	16 $MnSO_4$	16 $CaSO_4$	(b)	14.80 manganese	5.70 calcium.
78	8 $ZnSO_4$	8 $CdSO_4$	15	1.26 zinc	2.34 cadmium.
87	8 $NiSO_4$	8 $CaSO_4$	800	7.99 nickel	1.80 calcium.
90	20 $Fe(NO_3)_2$	20 $Pb(NO_3)_2$	1	2.40 iron	19.0 lead.
91	20 $Fe(NO_3)_2$	20 $Cu(NO_3)_2$	1	10.65 iron	10.20 copper.
92	20 $FeSO_4$	20 $CdSO_4$	1	2.90 iron	11.6 cadmium.
93	20 $ZnSO_4$	20 $FeSO_4$	1	15.80 zinc	4.2 iron.

a 18 hours. b 1 hour.

The results show that very rarely was a complete separation effected in the fractionation in the time allowed; in most of the experiments both metals were found in the precipitate and filtrate. The separations are far less sharp than those obtained with sulphides. The precipitation series deduced from these experiments is shown in the table below. The numbers in the third column indicate the ratio, in equivalents, of the predominating metal to the one in smaller amount in the precipitate. Not all the experiments have been made which could be made; conversely some of the orienting experiments were later seen to show little except that the two metals were widely separated in the series.

Precipitation series deduced from the experiments on fractional precipitation of carbonates and relative precipitation of the two metals.

Experiment.	Major constituent of precipitate.	Minor constituent of precipitate.	Ratio of major to minor constituent.
55	Mercury	Lead	Large.
31	do	Cadmium	2.1
25	do	Silver	3.5
59	Lead	Copper	Large.
90	do	Iron	6.5
23	do	Cadmium	19.0
24	do	Zinc	Large.
22	do	Silver	100.0
7, 91	Copper	Iron	1.0
8	do	Zinc	9.0
60	do	Cadmium	36.0
78	Cadmium	Zinc	1.9
92	do	Iron	4.0
67	do	Nickel	2.8
26	do	Silver	25.0
28	Zinc	do	2.5
27	do	Nickel	3.3
4	do	Calcium	6.5
71	do	Manganese	1.3
93	do	Iron	3.7
7	Iron	Copper	1.0
30	do	Zinc	1.0
29	do	Nickel	1.4
6	do	Calcium	6.3
34	Nickel	Manganese	1.1
33	do	Magnesium	Large.
87	do	Calcium	Do.
64	do	Silver	1.1
32, 74	Manganese	Calcium	4.0
41	Silver	do	4.4
42	Calcium	Magnesium	1.4

Incidental to the determination of relative solubility the experiments showed that metallic silver was precipitated with ferrous and manganous salts and there was also a very slight darkening of the precipitate with nickelous salt. The exact position of silver is therefore in some doubt, but it is certainly below zinc.

The positions of manganese and nickel are inconsistent with the recorded solubilities. Either the solubility of manganese carbonate should be less than that of calcium carbonate or there was oxidation of the manganese salt in experiment 70. Nickel shows a similar discrepancy.

The experiments further throw doubt on the solubility of ferrous carbonate given on page 29, although it must be said that the fractionations with ferrous sulphate were not very satisfactory. The difficulty was partly due to the ready oxidizibility of ferrous sulphate and partly to the apparent tendency of iron to enter into double compounds containing an atom of iron to one of the other metal. There is also a tendency toward the formation of bicarbonates, which is considered on page 37.

The heats of precipitation for the metallic carbonates are so small that no apparent regularity exists in the relation between the heats and the positions in the precipitation series.

RESULTS OF EXPERIMENTS WITH BICARBONATES.

The effect of basic carbonates on the fractionations and the elimination of this effect will now be considered. If in any precipitation of carbonate a hydroxide of one of the metals possesses such a small solubility that the hydrolysis of the carbonate would result in exceeding the solubility product of the hydroxide, more or less "basic salt" will be formed. These precipitates are ordinarily considered to be indefinite mixtures of hydroxide and carbonate, but it seems highly probable that either a pure carbonate, a hydroxide, or a definite basic salt would result if time were allowed for the attainment of equilibrium, for it has been shown that many days are often required for the attainment of a stable state at ordinary temperatures. This is another instance where the duration of the experiment determines the final product.

It is possible that a basic carbonate of one metal might form at the same time as a bicarbonate of another metal. There is some evidence of this in experiments 87, 92, and 93. In experiment 92 the mother liquor showed 1.1 milligram equivalents of HCO_3^-, and in experiment 93 it showed 5.3 milligram equivalents of HCO_3^- per liter.

In order to ensure that carbonates alone were being precipitated the experiments might have been carried out in the presence of a certain excess of carbon dioxide. As a much simpler means to the same end, however, a number of experiments were made with sodium bicarbonate as precipitating agent. The only difficulty encountered in this procedure was the rather large solubility of the bicarbonates of certain metals. The experiments were as follows:

Fractional precipitations with sodium bicarbonate.

Quantity taken (milligram equivalents).		Quantity precipitated (milligram equivalents).	
Experiment 35.			
$CuSO_4$	8.0	Copper	6.08
$ZnSO_4$	8.0	Zinc	5.84
$NaHCO_3$	8.0		
Time, 9 days.			
Experiment 36.			
$CdSO_4$	8.0	Cadmium	5.46
$ZnSO_4$	8.0	Zinc	1.60
$NaHCO_3$	8.0		
Time, 3 days.			
Experiment 37.			
$HgNO_3$	8.0	Mercury	7.54
$Zn(NO_3)_2$	8.0	Zinc	None.
$NaHCO_3$	8.0		
Time, 20 hours.			

Fractional precipitations with sodium bicarbonate—Continued.

Quantity taken (milligram equivalents).		Quantity precipitated (milligram equivalents).	
Experiment 38.			
$Pb(NO_3)_2$	8.0	Lead	7.82
$Cu(NO_3)_2$	8.0	Copper	0.16
$NaHCO_3$	8.0		
Time, 3 days.			
Experiment 44.			
$ZnSO_4$	8.1	Zinc	0.70
$FeSO_4$	8.0	Iron	4.36
$NaHCO_3$	8.0		
Time, 24 hours.			
Experiment 45.			
$ZnSO_4$	8.1	Zinc	2.14
$NiSO_4$	8.0	Nickel	0.82
$NaHCO_3$	9.0		
Time, 8 days.			
Experiment 46.			
$ZnSO_4$	8.0	Zinc	1.06
$AgNO_3$	8.0	Silver	2.90
$NaHCO_3$	8.0		
Time, 8 days.			
Experiment 47.			
$AgNO_3$	8.0	Silver	3.70
$MnSO_4$	8.0	Manganese	4.32
$NaHCO_3$	8.0		
Time, 11 days.			
Experiment 48.			
$ZnSO_4$	40.0	Zinc	12.1
$FeSO_4$	40.0	Iron	21.2
$NaHCO_3$	40.0		
Time, 20 hours.			
Experiment 51.			
$FeSO_4$	32.0	Iron	9.16
$MnSO_4$	32.0	Manganese	21.92
$NaHCO_3$	22.0		
Time, 1 day.			
Experiment 52.			
$CuSO_4$	8.0	Copper	5.64
$CdSO_4$	8.0	Cadmium	0.40
$NaHCO_3$	8.0		
Time, 5 days.			
Experiment 53.			
$HgNO_3$	8.0	Mercury	Nearly all.
$Pb(NO_3)_2$	8.0	Lead	Trace.
$NaHCO_3$	8.0		
Time, 5 days.			

Fractional precipitations with sodium bicarbonate—Continued.

Quantity taken (milligram equivalents).		Quantity precipitated (milligram equivalents).	
Experiment 54.			
$HgNO_3$	8.0	Mercury	Nearly all.
$Cd(NO_3)_2$	8.0	Cadmium	Trace.
$NaHCO_3$	8.0		
Time, 4 days.			
Experiment 57.			
$CdSO_4$	8.0	Cadmium	7.60
$MnSO_4$	8.0	Manganese	5.96
$NaHCO_3$	8.0		
Time, 5 days.			
Experiment 72.			
$ZnSO_4$	16.0	Zinc	6.84
$MnSO_4$	16.0	Manganese	10.24
$NaHCO_3$	16.0		
Time, 18 hours.			
Experiment 88.			
$NiSO_4$	16.0	Nickel	1.88
$CaSO_4$	16.0	Calcium	0.20
$NaHCO_3$	16.0		
Time, 5 days.			

Summary of results of fractional precipitation with sodium bicarbonate at 15°–20° C., arranged in the order of solubility deduced from the experiments.

Experiment.	Major constituent of precipitate.	Minor constituent of precipitate.	Ratio of major to minor constituent.
53	Mercury	Lead	(a)
54	do	Cadmium	(a)
37	do	Zinc	(a)
38	Lead	Copper	49.0
52	Copper	Cadmium	14.0
50	do	Ferrous iron	1.6
35	do	Zinc	1.0
57	Cadmium	Manganese	1.3
49	do	Ferrous iron	6.4
36	do	Zinc	3.4
89	do	Silver	92.0
51	Manganese	Ferrous iron	2.5
72	do	Zinc	1.5
46	Silver	do	2.7
44, 48	Ferrous iron	do	1.7
45	Zinc	Nickel	2.6
88	Nickel	Calcium	9.4
	Calcium		
	Magnesium		

[a] Chiefly mercury.

From these results it appears that when bicarbonates are used instead of carbonates the principal changes are that ferrous iron, zinc, and nickel fall below silver in the series.

EXPERIMENTS WITH CARBONATES AT HIGHER TEMPERATURES.

At 100° C. bicarbonates are no longer stable at low pressures, although the last traces of carbon dioxide are held very tenaciously by solutions containing calcium or magnesium salts. Under high pressures of carbon dioxide and at elevated temperatures the bicarbonates would no doubt persist. The compounds stable under these conditions, however, and their solubilities remain to be determined. A few solubilities have been measured in solutions saturated with carbon dioxide at a pressure of a few atmospheres, but mostly at ordinary temperatures. The crystallization of dolomite at 150° C. has been noted. Of course many of the metallic carbonates become basic as the temperature rises, as has already been stated, and some lose carbon dioxide on boiling. Hence in most of the experiments the precipitation was made cold and the flask and contents then heated to 60°–80° C.

In experiment 16 a solution containing 5.43 milligram equivalents of cadmium sulphate and 5.43 milligram equivalents of zinc sulphate was precipitated with 5.43 milligram equivalents of sodium carbonate in a volume of 250 cubic centimeters. After boiling three hours the precipitate contained 4.76 milligram equivalents of zinc and 0.60 milligram equivalents of cadmium.

In experiment 18 a solution containing 8 milligram equivalents of nickel carbonate was boiled one hour with 8 milligram equivalents of calcium sulphate. No nickel dissolved.

In experiment 20 a solution containing 8.81 milligram equivalents of cadmium sulphate and 8.81 of nickel carbonate was boiled five hours in the presence of 8.81 milligram equivalents of sodium sulphate. A small amount of cadmium was precipitated.

In experiment 66 the attempted fractionation of manganese sulphate and silver nitrate resulted in a reduction of the silver salt and oxidation of the manganese.

In experiment 70 the precipitate formed from the sulphates of manganese and calcium turned brown in about a quarter of an hour, showing a slight oxidation of the manganese.

Further results follow.

Fractional precipitations with sodium carbonate at 60°–80° C.

Quantity taken (milligram equivalents).		Quantity precipitated (milligram equivalents).	
Experiment 78.			
$Hg(NO_3)_2$	16.0	Mercury	8.88
$Pb(NO_3)_2$	16.0	Lead	5.2
Na_2CO_3	16.0		
1 hour at 60° C.			
Experiment 79.			
$Pb(NO_3)_2$	16.0	Lead	10.24
$Cu(NO_3)_2$	16.0	Copper	6.68
Na_2CO_3	16.0		
1 hour at 80° C.			
Experiment 80.			
$Ag(NO_3)_2$	12.0	Silver	11.00
$MgSO_4$	12.0	Magnesium	.40
Na_2CO_3	12.0		
1 hour at 70° C.			
Experiment 82.			
$ZnSO_4$	16.0	Zinc	13.80
$FeSO_4$	16.0	Iron	4.72
Na_2CO_3	16.0		
1 hour at 70° C.			
Experiment 83.			
$CdSO_4$	16.0	Cadmium	14.32
$FeSO_4$	16.0	Iron	2.04
Na_2CO_3	16.0		
1 hour at 70° C.			
Experiment 84.			
$FeSO_4$	16.0	Iron	0.68
$NiSO_4$	16.0	Nickel	10.0
Na_2CO_3	18.0		
1 hour at 70° C.			
Experiment 85.			
$CaSO_4$	12.0	Calcium	Undetermined.
$FeSO_4$	12.0	Iron	8.44
Na_2CO_3	12.0		
1 hour at 70° C.			
Experiment 86.			
$CuSO_4$	16.0	Copper	9.08
$FeSO_4$	16.0	Iron	6.72
Na_2CO_3	16.0		
1 hour at 70° C.			

These results are collected in the following table:

Summary of results of fractional precipitation with sodium carbonate at 60°–80° C., arranged in the order of solubility deduced from the experiments.

Experiment.	Major constituent of precipitate.	Minor constituent of precipitate.	Ratio of major to minor constituent.
78	Mercury	Lead	1.7
76	do	Copper	4.5
59, 62, 79	Lead	do	1.5
15	Copper	Cadmium	3.6
86	do	Ferrous	1.4
17	do	Silver	2.1
77	Zinc	Cadmium	1.1
82	do	Iron	2.9
67	Cadmium	Nickel	2.7
83	do	Iron	7.0
84	Nickel	do	15.0
73	do	Calcium	10.0
65	do	Silver	17.0
94	do	Manganese	1.0
85	Iron	Calcium	
95	Manganese	do	Chiefly manganese.
75	Calcium	Silver	1.5
80	Silver	Magnesium	27.0
	Magnesium		

The results at higher temperatures show only minor changes from the series at ordinary temperatures. Zinc appears above cadmium, probably owing to the formation of oxide. Nickel appears above iron, but as there is some doubt about their relative positions in the series at ordinary temperatures, this change is not to be emphasized. This shows that the experiments at ordinary temperatures yield conclusions of fundamental significance.

In experiment 86 the ferrous iron was partly oxidized, presumably at the expense of cupric sulphate. Of the iron in the filtrate 24 per cent was in the ferric condition. The experiments with ferrous salts were all made in a special precipitating flask in an atmosphere of hydrogen, so that oxidation by air was sufficiently avoided.

SUMMARY OF RESULTS OF EXPERIMENTS WITH CARBONATES.

1. Calcite introduced into a dilute solution of zinc sulphate precipitates the zinc slowly, requiring two or three weeks to precipitate most of the zinc.

2. Freshly precipitated calcium carbonate acts more rapidly in precipitating metallic salts than any other form, and aragonite and calcite follow in the order named.

3. The precipitating action of calcite on manganese, nickel, and silver salts is less marked than on zinc, cadmium, copper, lead, and mercury salts.

4. When a mixture containing two equivalents of two metallic salts, one equivalent of each, is precipitated by one equivalent of a soluble carbonate, a fractionation occurs, and the extent of this fractionation has been determined approximately for a large number of substances.

5. The series obtained, beginning with the metals precipitated to the greatest extent, with sodium carbonate at ordinary temperature is mercury, lead, copper, cadmium, zinc, ferrous iron, nickel, manganese, silver, calcium, magnesium.

6. The series obtained with sodium bicarbonate at ordinary temperature is mercury, lead, copper, cadmium, manganese, silver, ferrous iron, zinc, calcium, magnesium.

7. The series obtained in warm solutions with sodium carbonate is mercury, lead, copper, zinc, cadmium, nickel, iron, calcium, silver, magnesium.

8. Silver salts are partly reduced by ferrous and manganous salts; possibly also by nickelous salts, this effect becoming more marked as the alkalinity increases.

9. In the presence of bicarbonates zinc shows relatively greater solubility than cadmium, and nickel is likewise relatively more soluble than when precipitated with normal carbonate.

10. With rising temperature the precipitates from cadmium, iron, and silver salts appear to increase in solubility relatively faster than the others.

11. The presence of cupric sulphate greatly intensifies the tendency of ferrous salts to oxidize.

SILICATES.

PREVIOUS WORK.

Since many of the natural silicates have been formed under the condition of equilibrium with a magma it is obvious that they will not be in equilibrium with aqueous solutions. In order to complete the study of fractional precipitation, however, it appeared desirable to see if there would be any selective action when solutions containing more than one metallic salt were precipitated by a soluble silicate. Jordis has already studied the precipitation of single metallic silicates from soluble salts [1] with reference to their composition. His experiments with ferric salts,[2] however, are probably complicated by the phenomena of hydrolysis, but he suggests that the behavior of colloids must be considered.

EXPERIMENTS WITH SILICATES AT ORDINARY TEMPERATURE.

My own experiments have consisted of attempts at fractional precipitations of metallic salt solutions by amounts of soluble silicates insufficient for both the metallic constituents. Although it was expected that the sodium silicate, being hydrolyzed, would behave like

[1] Jordis, Eduard, Zur Chemie der Silikate: Zeitschr. angew. Chemie, vol. 19, p. 1697, 1906; Jour. prakt. Chemie, vol. 77, pp. 226-261, 1906; idem, vol. 81, p. 303, 1910.

[2] Jordis, Eduard, and Lincke, P., Beiträge zur Kenntnis der Metall-Silicate: Jour. prakt. Chemie, vol. 81, p. 289, 1910.

caustic soda, it seemed desirable to determine whether the silicic acid would participate in the reaction. After the results with the hydroxides, it was not surprising to find that in general one metal was precipitated to a greater extent than the other. Moreover, most of the silica was carried down with the precipitate. The results are shown in the following table, where the concentrations are expressed in millimoles per liter, one millimole being a thousandth of the molecular weight taken in grams. A diluted water-glass solution was used as the soluble silicate. The ratio of SiO_2 to Na_2O in it was 3.09 to 1.00. It was free from other metals except for a trace of iron and alumina. After precipitation the solutions stood at about 30° C. for the periods noted in the table. The last column in the table shows the silica not precipitated by the metallic salts present. Sulphates were used except with lead and calcium salts, where nitrates were employed.

Results of the fractional precipitation of silicates, arranged in the order of the solubility deduced from the experiments.

Experiment.	Time (days).	Quantities precipitated (millimoles).	SiO_2 not precipitated (millimoles).
114	97	4.8 copper, 0.2 lead, 11.2 SiO_2	4.0
115	91	6.7 copper, 0.7 zinc, 12.8 SiO_2	2.4
116	91	6.6 copper, no cadmium, 12.2 SiO_2	3.0
117	107	8.1 zinc, 5.6 manganese, 13.0 SiO_2	3.2
118	97	5.1 zinc, 0.1 silver, 11.9 SiO_2	3.3
119	31	5.1 zinc, 2.6 nickel, 10.5 SiO_2	4.7
120	102	5.9 manganese, 4.2 cadmium, 12.9 SiO_2	2.3
121	31	Very little cadmium and zinc, 12.5 SiO_2	2.7
122	95	5.13 nickel, no calcium, 12.9 SiO_2	2.8
123	97	4.8 magnesium, 0.2 calcium, 13.0 SiO_2	2.2
[a] 124	95	13.0 nickel, 0.8 calcium, 28.1 SiO_2	2.8
[a] 125	95	10.7 magnesium, 2.9 calcium, 27.6 SiO_2	2.8

[a] Double quantities taken.

Quantities taken in each experiment:
9.10 millimoles M_1SO_4 per liter of the mixture.
9.10 millimoles M_2SO_4 per liter of the mixture.
4.95 millimoles Na_2O, 15.2 millimoles SiO_2 per liter of the mixture.

SUMMARY OF RESULTS OF EXPERIMENTS WITH SILICATES.

From the above results it appears that:

1. The order of precipitability of the metals by soluble silicate solutions is roughly as follows, beginning with the most precipitable: Copper, zinc, manganese, cadmium, lead, nickel, silver, magnesium, calcium.

2. The metals are precipitated almost as they would be by solutions of caustic soda, so that no marked specific effect appears to be due to the presence of the silicate.

3. Most of the silica is precipitated.

4. Some silica remains in solution, even with an excess of the metallic salt, and the quantity that remains appears to be independent of the nature of the metallic salt.

GENERAL VIEW OF THE RESULTS OF THE INVESTIGATION.

For comparison the several series obtained in the study of fractional precipitation in aqueous solution have been brought together in the following table:

Order of solubility for each class of compounds deduced from these experiments on fractional precipitation.

Sulphides.	Carbonates.	Bicarbonates.	Hydroxides.	Silicates.
Palladium			Ferric	
Mercury	Mercury	Mercury	Aluminum	
Silver	Lead	Lead		
Copper	Copper	Copper	Copper	Copper.
Bismuth				
Cadmium	Cadmium	Cadmium		
Antimony				
Tin	Zinc		Zinc	Zinc.
Lead			Lead	Manganese.
Zinc				Cadmium.
Nickel	Iron			Lead.
Cobalt				
Ferrous	Nickel		Nickel	Nickel.
Arsenic				
Thallium	Manganese	Manganese		
Manganese	Silver	Silver	Silver	Silver.
		Ferrous	Ferrous	
		Zinc	Manganese	
	Calcium	Calcium	Magnesium	Magnesium.
	Magnesium	Magnesium	Calcium	

It would be possible to work out still other series by fractional precipitation. For example, the series of chlorides would be relatively short, whereas that of the phosphates would be longer, for most phosphates are insoluble. The compounds studied, however, cover the ordinary geologic transformations and the studies show the general relations. Furthermore, in the tabulation of the results no attempt has been made to do more than arrange the several series in parallel columns. By a scheme that would exhibit cross relations all possible compounds might be arranged in a single series that would show the order of precipitation under like conditions. Such a series, however, would have little practical application, for several reasons. A comparison of two compounds with no common radicle would really imply the possible existence of at least four compounds, a degree of complexity greater than that considered in the present study of fractional precipitation. Furthermore, the effects of mass action are always conjoined with the solubility requirements, a fact illustrated by the relations of certain silver haloids at Tonopah, Nev.[1] In this locality silver chloride, cerargyrite, was deposited before the chlorobromide, embolite, and the

[1] Burgess, J. A., The halogen salts of silver and associated minerals at Tonopah, Nev.: Econ. Geology, vol. 6, p. 13, 1911.

iodide, iodyrite, which is more insoluble than the cerargyrite, probably because of the great excess of chlorides in the original solution. This series well illustrates the application of the mass law. Silver iodide is more insoluble in water than silver chloride, but if a solution of a silver salt meets a solution containing a great deal of chloride and very little iodide, after mixing (it being assumed for argument that precipitation does not occur instantaneously) the silver ion concentration will have a fixed value, the chloride ion concentration will be very large, and the iodide ion concentration very small. Hence the solubility product of silver chloride will be exceeded and that of silver iodide not be exceeded, although the solubility product of silver chloride is larger than that of silver iodide. Silver chloride may therefore be deposited before silver iodide, in apparent contradiction to the stated solubilities of the two compounds in water. On the other hand, the solubility of a compound in water is one of its most important properties, and it was to determine the order of these solubilities that these experiments on fractional precipitation were made.

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MINERALOGIC NOTES, SERIES 3.

By WALDEMAR T. SCHALLER.

INTRODUCTION.

The results of the smaller, independent pieces of mineralogic research work carried out by the writer in the chemical laboratory of the United States Geological Survey from July 1, 1911, to December 31, 1913, are here assembled. Earlier reports of a similar nature have been published as "Mineralogical notes" (1903–4), in Bulletin 262, 1904; "Mineralogical notes, series 1" (1905–1909), as Bulletin 490, 1911; and "Mineralogical notes, series 2" (1910–11), as Bulletin 509, 1912. In addition to these papers a report on the crystallography of ferberite from Colorado was revised for publication in Bulletin 583, and a report on the gem tourmaline field of southern California has been submitted for publication as Professional Paper 92.

The writer spent the summer of 1912 in Europe and obtained a considerable amount of valuable material, especially from the collection in the Vienna Hof-Museum, and the results of study of two minerals thus obtained—koechlinite, a new species, and schneebergite, analyzed completely for the first time—are here presented. The papers on custerite and on hodgkinsonite were first published in conjunction with other investigators, and their contributions have been briefly summarized in the present notes.

The papers preceding the one on the crystallography of fremontite, except the one entitled "The composition of cebollite," have not been previously published.

KOECHLINITE (BISMUTH MOLYBDATE), A NEW MINERAL.

ORIGIN OF INVESTIGATION.

Some years ago the writer[1] described a crystallized bismuth mineral from Nevada which occurred in hexagonal rhombohedral crystals and was optically uniaxial. Analysis of this mineral showed the presence of considerable water, and in accordance with the results obtained on bismuth ocher from California[2] the mineral from Nevada was considered to have the composition expressed by the formula $Bi_2O_3.3H_2O$. The crystals from Nevada are very different from those assigned to the anhydrous oxide of bismuth, Bi_2O_3, as given in Dana's Mineralogy.[3] It seems doubtful, therefore, whether the anhydrous oxide exists in nature as such, and a sharp outlook has been kept for natural occurrences of crystallized Bi_2O_3.

While the writer was at Vienna in 1912 he made an inquiry as to the presence of such specimens in the collections, and the custodian of the mineral collection of the Hof-Museum, Dr. Rudolf Koechlin, called particular attention to a specimen showing small greenish rectangular crystals which had been supposed to be torbernite but which Dr. Koechlin had found to give a strong bismuth reaction. On request, and on the approval of Dr. F. Berwerth, director of the mineralogic and petrographic division of the Hof-Museum, part of the specimen was given to the writer for study, and it is a great pleasure for him to express his thanks for the kindness and liberality of Drs. Berwerth and Koechlin in furnishing this valuable material.

The investigation showed that the mineral contained essentially only the oxides of bismuth and molybdenum, and the analyses yielded results from which the simple formula $Bi_2O_3.MoO_3$ was deduced.

The acquisition of the specimen by the Vienna Museum is thus described by Dr. Koechlin. The specimen was bought in 1884 from a Mr. Kulda who carried on a small trade in natural-history objects. The specimen of koechlinite, No. D. 3478 in the Vienna catalogue, was labeled torbernite. As Dr. Koechlin had found considerable bismuth in the mineral, however, it had been relabeled bismuth ocher. According to him the mineral somewhat resembles uranospinite. The only observed phase of the mineral consists of sharp, minute tabular crystals which are described in detail below, under the heading "Crystallography."

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[1] Schaller, W. T., Bismite from Nevada: U. S. Geol. Survey Bull. 490, p. 33, 1911. Compare also Ransome, F. L., The geology and ore deposits of Goldfield, Nev.: U. S. Geol. Survey Prof. Paper 66, p. 121, 1909.

[2] Schaller, W. T., Bismuth ochers from San Diego County, Cal.: Am. Chem. Soc. Jour., vol. 33, p. 162, 1911.

[3] Dana, E. S., System of mineralogy, 6th ed., p. 200, 1892.

NOMENCLATURE.

The services of Dr. Rudolf Koechlin, both as investigator and as custodian of the mineral collection in Vienna, are too well known to call for any extended remarks, and in proposing the name koechlinite for the new bismuth molybdate herein described the writer takes a double pleasure, for not only the scientific attainments of Dr. Koechlin are thereby recognized, but in addition his charming personality and great willingness to help others, which were so manifest during the writer's stay in Vienna.

The formula of koechlinite is a simple one, but no other minerals were noted with which it could be closely related, and for the present it must be placed with other molybdates, although from analogy one might expect to find minerals similar in type but differing chemically, as, for example, the unknown compound $Fe_2O_3.SO_3$.

LOCALITY.

The locality as given originally by Mr. Kulda is the Daniel mine, Schneeberg, Saxony, Germany, and the already long list of secondary bismuth minerals found at this classic locality is now further extended.

PARAGENESIS.

The character of the matrix and its geologic relations are not known, but the specimens appear typically like parts of a mineralized quartz vein, rich in cavities lined with well-developed quartz crystals, upon which rest the crystals of koechlinite.

The associated minerals are massive white quartz and quartz in colorless crystals, forming the main part of the specimen; abundant native bismuth, in cleavable masses, in part strongly iridescent; abundant smaltite, in cubic crystals ({100}, {111}) about 1 millimeter thick (wrongly described as chloanthite by Mr. Kulda); a red mineral (realgar?) occurring sparsely as minute seams in the massive quartz; a few needle-like prisms of a gray metallic mineral (bismuthinite?, stibnite?) in the cavities with koechlinite; and three unidentified minerals found directly associated with the koechlinite.

The contents of some of the cavities were removed, and the larger crystals were picked out for measurement and analytical purposes. The remaining fine material was then embedded in cooked balsam dissolved in chloroform, which was then allowed to harden by gradual evaporation of the chloroform. The material in these microscopic slides was therefore not subjected to any heat. Many perfect crystals of koechlinite were found in this fine material, and their habit and optical properties could be well studied under the microscope. A group of three such crystals in parallel position is shown in figure 1. The very high index of refraction of the mineral gives all the crystals a thick black border, due to total reflection. The

striations on the tabular crystals are vertical and the bounding faces of the crystals are those of the unit pyramid. The angle of the edges (111)–$(\bar{1}11)$: $(1\bar{1}1)$–$(\bar{1}\bar{1}1)$ is 90° 08′, thus giving the rectangular shape to the crystals.

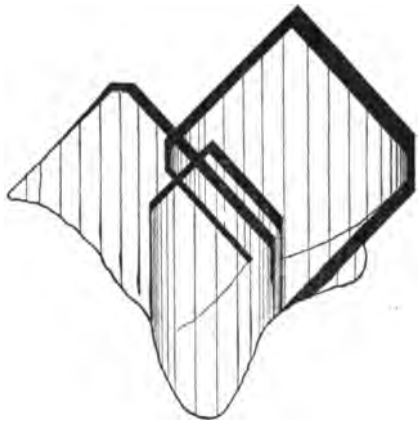


FIGURE 1.

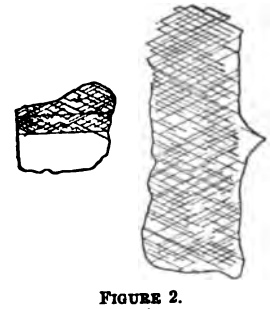


FIGURE 2.

FIGURE 1.—A group of three crystals of koechlinite in parallel position. The heavy black border is caused by total reflection due to the very high refractive index of the mineral.
FIGURE 2.—Sketch of unknown mineral A associated with koechlinite.

The associated minerals became concentrated in the material forming the slides by the removal of the larger koechlinite crystals, and the description of these associated minerals is based entirely on the microscopic observations made on the slides.

The metallic associaets have already been given. Besides quartz, three nonmetallic minerals, none of which could be identified, were observed with the koechlinite. It does not necessarily follow, however, that any of them are new. For convenience of description these three associated minerals are called unknown A, B, and C, respectively.

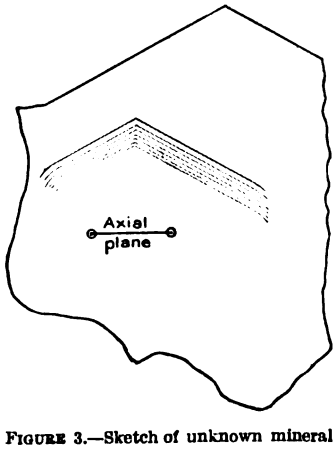


FIGURE 3.—Sketch of unknown mineral B associated with koechlinite.

Unknown mineral A was observed in about half a dozen pieces. Nearly all of them have an irregular outline which in small part is bounded by cleavage directions. A single fragment showed one apparently straight outline, bisecting the cleavage lines. The cleavage is very prominent and permeates the entire mineral, breaking up the fragment into numerous rhombs with an acute angle of about 52°. Figure 2 is a diagrammatic sketch of two such fragments. The color of the transparent and isotropic mineral is a light to dark brown. No interference figure could be obtained from any of the fragments.

Unknown mineral B is abundant as small mica-like scales, which for the most part are devoid of any regular outline, although here and there are scales that have a more or less regular boundary. The most perfect of these have a hexagonal shape and extinguish parallel to one pair of sides. One of the larger fragments observed is sketched in figure 3. The two straight sides at the top are inclined to each other at an angle of about 57°, and each was inclined about 62° to the extinction. The mineral is colorless and transparent and has a moderate to low double refraction. The parallel markings shown are parallel to the two straight sides. The axial angle is small and negative.

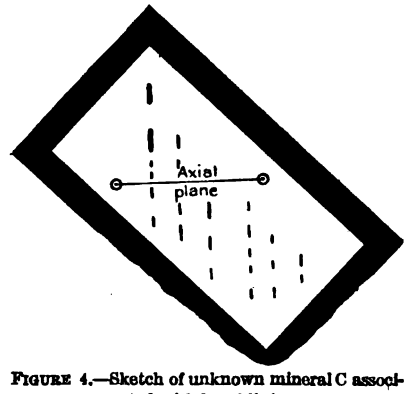


FIGURE 4.—Sketch of unknown mineral C associated with koechlinite.

Unknown mineral C was observed about a dozen times, either as well-formed isolated crystals or intergrown with koechlinite. The crystals have the same shape and orientation as those of koechlinite and consist of the macropinacoid {100} large, bounded by faces of the unit pyramid {111}. The crystals of unknown mineral C are at once distinguished from koechlinite by their lack of color and much lower double refraction. The very high index of refraction and the comparative thickness gives these crystals a very broad border of black, due to total reflection, as shown in figures 4 and 5. They have a more constant habit than koechlinite, nearly all of them being about twice as long as wide. The vertical striations are not prominent, and one crystal showed vertical lines of minute inclusions, as shown in figure 4, which well illustrates the shape and appearance of the crystals. The crystals of unknown mineral C are twinned similarly to those of koechlinite. One crystal, between crossed nicols, showed a complex twinning (as illustrated in fig. 5) very similar in kind to that exhibited by koechlinite and shown in figure 20 (p. 24).

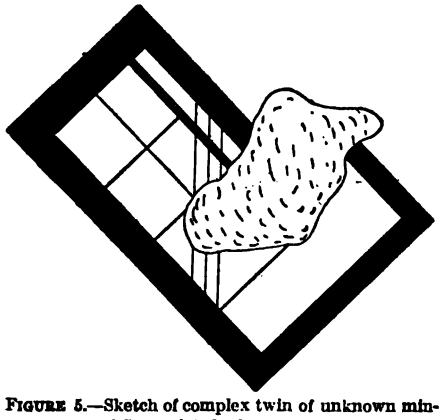


FIGURE 5.—Sketch of complex twin of unknown mineral C associated with koechlinite.

The crystals of unknown mineral C have a low birefringence, the interference colors being generally of the first order, even on the thicker crystals, whereas the thinnest cleavage plates of koechlinite seldom

show colors below the third order. The axial plane of unknown mineral C is parallel to $c\{001\}$, as in koechlinite, and the axial angle is very large, $2E$ being greater than the field of the microscope.

Koechlinite is clearly a secondary mineral formed in the cavities of the quartz rock by the reaction of different solutions, one containing bismuth and the other molybdenum. Some of the cavities lined with quartz crystals are free from any other mineral.

CRYSTALLOGRAPHY.

GENERAL CHARACTER OF CRYSTALS.

All the koechlinite occurs in distinct crystals. Eight of these were measured on the goniometer, but in addition a large number were examined under the microscope, for with the knowledge obtained from the goniometer measurements the combinations of the crystals seen under the microscope could be easily deciphered. The crystals measured average about 0.5 millimeter in greatest length. The crystals on the specimens range in size from minute ones to those having a length of about 1 millimeter. The width of the crystals is either equal to or about half the length, and the third dimension is very small, as the crystals are all very thin and tabular in habit.

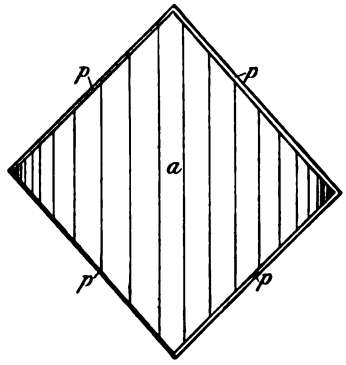


FIGURE 6.—Common appearance of crystals of koechlinite, simulating rectangular plates. Forms: $a\{100\}$, $p\{111\}$.

The combinations observed on many of the crystals are simple, and in fact most of the crystals show only two or three forms. The general appearance of the crystals is shown in figure 6, and as the angle between the opposite pyramids is nearly 90°, the crystals appear as rectangular plates with diagonal striations. A marked feature of these crystals which heightens the impression that they are rectangular plates is a tendency for distortion in that the crystal is elongated parallel to one of the intersection directions of $a\{100\}$ with $p\{111\}$, thus producing the effect shown in figure 7.

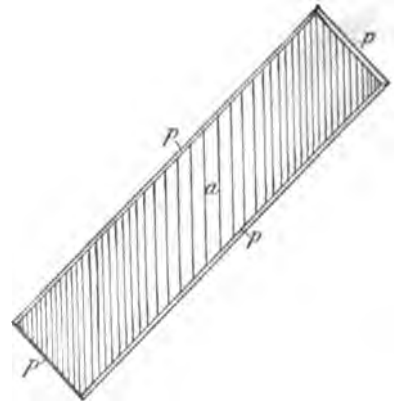


FIGURE 7.—Distorted crystal of koechlinite, elongated parallel to one of the intersected directions of $a\{100\}$ with $p\{111\}$.

Apparently the crystals should be so oriented that the edges $a\{100\}$: $p\{111\}$ are vertical and horizontal, but the direction of the striations on $a\{100\}$ shows the true position, which is verified by the angle measurements. The crystals are both simple and twinned.

CALCULATION OF ELEMENTS.

The crystals of koechlinite are orthorhombic, and the measurements of the unit pyramid are utilized for the calculation of the elements. The prism zone being vertically striated, the crystals were readily adjusted in polar position, and measured on the two-circle goniometer. The value for v_0 was found by averaging the readings on $a\{100\}$ and the theoretic readings on $b\{010\}$ obtained by averaging the corresponding pairs of v readings of the unit pyramids $\{111\}$. The signals reflected from the large faces of $a\{100\}$ were sharp and bright, whereas those from the very narrow pyramid faces were mostly faint and not very distinct. The measurements on five crystals show fairly good agreement, though future measurements of larger and better crystals would doubtless yield more accurate results. The values obtained are as follows:

Measurements of unit pyramid.

Crystal 1.		Crystal 2.		Crystal 5.		Crystal 7.		Crystal 8.	
ϕ	ρ	ϕ	ρ	ϕ	ρ	ϕ	ρ	ϕ	ρ
° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
45 42	55 02	45 40	55 07	45 26	55 00	45 20	55 59	46 10	54 58
45 27	54 55	45 42	55 10	45 47	55 05	45 51	55 04	45 48	54 59
45 26	55 08	45 27	55 01	45 49	55 09	45 58	55 10	47 34	54 59
45 38	55 21	45 50	55 08	45 36	55 05	45 48	54 33	45 03	55 20

From the average of these measurements the values $p_0=1.0258$, $q_0=1.0026$, and the axial ratio $a : b : c=0.9774 : 1 : 1.0026$ are obtained. The axial ratio of koechlinite is very close to the 1 : 1 : 1 ratio of the isometric system, but in its tabular habit and perfect cleavage parallel to $a\{100\}$, the mineral differs greatly from one of isometric character.

FORMS AND ANGLES.

A total of 13 forms was determined on the crystals of koechlinite. These are as follows:

Pinacoids: $b\{010\}$, $a\{100\}$.
Prisms: $l\{130\}$, $n\{230\}$, $j\{450\}$, $m\{110\}$, $h\{430\}$, $k\{210\}$.
Pyramids: $p\{111\}$, $r\{322\}$, $s\{533\}$, $u\{131\}$, $x\{362\}$.

The average of the measured angles as compared with the calculated values is shown in the following list:

Measured and calculated angles of koechlinite.

No.	Letter.	Symbol.		Measured.				Calculated.			
		Goldschmidt.	Miller.	ϕ		ρ		ϕ		ρ	
				°	′	°	′	°	′	°	′
1	*b*	0∞	010	0	29	90	00	0	00	90	00
2	*a*	$\infty 0$	100	90	00	90	00	90	00	90	00
3	*l*	$\infty 3$	130	17	46	90	00	18	50	90	00
4	*n*	$\infty \frac{3}{2}$	230	34	55	90	00	35	32	90	00
5	*j*	$\infty \frac{5}{4}$	450	39	20	90	00	39	18	90	00
6	*m*	∞	110	44	09	90	00	45	39	90	00
7	*h*	$\frac{4}{3}\infty$	430	53	10	90	00	53	45	90	00
8	*k*	2∞	210	65	07	90	00	63	57	90	00
9	*p*	1	111	45	39	55	07	45	39	55	07
10	*r*	$\frac{3}{2}1$	322	55	56	60	54	56	55	61	26
11	*s*	$\frac{5}{3}1$	533	58	55	62	55	59	37	63	14
12	*u*	13	131	18	22	72	09	18	50	72	32
13	*x*	$\frac{3}{2}3$	362	27	13	73	21	27	06	73	31

a{100}. The macropinacoid, parallel to which there is a good cleavage, is the dominant form of koechlinite, and all the crystals are tabular parallel to this form. The faces are vertically striated. Nearest the prism faces the striations become prominent enough to round the face and to give a blurred distended reflection, but the larger part of the face gives a bright and clear reflection. The macropinacoid and the unit pyramid are the only two forms which were observed on all the crystals examined.

b {010}. The brachypinacoid was observed on four crystals, as small and narrow faces. The reflections were very poor and the ϕ measurements gave $-0°07'$, $+0°22'$, $+2°06'$, $-0°27'$, instead of $0°00'$. On crystal 8 the face was uneven and vertically striated.

l {130}. The single face of this form is a short line face giving a very poor reflection.

n {230}. The prism *n* is the third most prominent form, and although it was observed on only five of the eight measured crystals, it was determined to be present on many of the crystals studied microscopically. In fact, it is the dominant prism form of the mineral, many crystals showing only the three forms *a*, *p*, *n*. (Compare figs. 12, 13, and 14, on pp. 21, 22.) The measurements of this form are as follows:

Measurements of ϕ angle of n{230}.

Crystal No.	Size.	Reflection.	Measured.		Calculated.	
			°	′	°	′
1	Minute	Glimmer [a]	34	18	35	32
1	do	do	34	50	35	32
1	do	do	33	03	35	32
2	Short, broad line face.	Poor	36	22	35	32
5	Line face	Glimmer [a]	36	04	35	32
5	do	do	36	09	35	32
6	do	do	37	42	35	32
6	do	do	33	03	35	32
6	do	Poor	35	00	35	32
7	do	Glimmer [a]	33	13	35	32
7	Broad line face.	Poor	34	26	35	32

[a] Measured by position of brightest illumination, which was generally only a glimmer.

j {450}. The two observed faces of *j* are mere line faces giving an exceedingly faint reflection. The measured ϕ angles (39°22′ and 39°18′) agree well with each other and with the calculated angle (39°18′).

m {110}. The unit prism was seen only once as a line face giving a poor reflection.

h {430}. The four faces of *h*, observed on as many crystals, are all line faces giving poor reflections. The measured ϕ angles are 51°41′, 52°33′, 53°41′, 54°46′ (calculated 53°45′).

k {210}. The single face of *k* is a line face yielding only a glimmer of light.

p {111}. The unit pyramid is the dominant terminal form, and is present on all crystals examined. It is as a rule long and narrow, rarely becoming broader, whereby the whole crystal becomes thicker. It is striated in the zone (100): (111): ($\bar{1}$11): ($\bar{1}$00).

r{322}. This pyramid occurs as a very narrow line face between *a* and *p*. The reflections were considerably distended on account of the minute width of the faces, and they could not be measured with great accuracy. The form was definitely determined on only one crystal (No. 2) but is probably present on some of the other crystals. The measured angles are as follows:

ϕ meas. = 56°33′ ϕ calc. = 56°55′. ρ meas. = 61°10′ ρ calc. = 61°26′.
ϕ meas. = 55°19′ ρ meas. = 60°37′

s{533}. The faces of *s*, like those of *r*, are the merest line faces, and their measurements are likewise not very accurate. The form was identified positively on four crystals but may be present on several more. The two forms *r*{322} and *s*{533} were not both determined on the same crystal. The measurements for *s* are given in the following table:

Measurements of s{533}.

Crystal No.	Measured.		Calculated.	
	ϕ	ρ	ϕ	ρ
	° ′	° ′	° ′	° ′
5	59 09	63 32	59 37	63 14
5	58 52	62 50	59 37	63 14
5	58 48	62 50	59 37	63 14
5	59 23	62 50	59 37	63 14
7	58 57	62 37	59 37	63 14
8	58 22	62 50	59 37	63 14

The following interfacial angles were measured on crystal 3. Only *a*{100} gave good reflections.

Interfacial angles measured on crystal 3 of koechlinite.

Angle.	Measured.	Calculated.
	° ′	° ′
$a:p=(100):(111)$	54 27	54 05
$a':p'=(\bar{1}00):(1\bar{1}1)$	54 10	54 05
$a':p''=(\bar{1}00):(\bar{1}\bar{1}1)$	54 00	54 05
$a:p'''=(100):(\bar{1}\bar{1}1)$	54 05	54 05
$a:s=(100):(533)$	40 08	39 38
$p:s=(111):(533)$	13 52	14 27
$p:r=(111):(322)$	.....	11 28

u{131} and *x*{362}. These two pyramids were measured only once, both forms showing a well-developed face on crystal 7 (fig. 28, p. 26). It is believed that additional occurrences of these forms were seen on other crystals under the microscope, but they could not be positively identified. On crystal 7 the face of *u*(131), although striated somewhat in the zone *u a*, gave a fair reflection. The face of *x*(362) is a line face between *u* and *a* and gave a poor reflection. The measured and calculated angles (given on p. 16) agree well.

From their occurrence the thirteen forms may be grouped as follows:

Common forms: *a*{100}, *p*{111}, *n*{230}.
Less common forms: *b*{010}, *h*{430}, *j*{450}, *s*{533}.
Rare forms: *m*{110}, *l*{130}, *k*{210}, *r*{322}, *u*{131}, *x*{362}.

COMBINATIONS.

The combinations observed on the eight crystals measured are shown in the following table:

Combinations of koechlinite crystals.

Form.	Crystal No.								Percentage of occurrence.	Illustrated in figures—
	1	2	3	4	5	6	7	8		
a{100}	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	100	6, 7, 11–14, 21, 23–29.
b{010}	*b*	....	....	*b*	....	....	*b*	*b*	50	11, 28.
l{130}	....	....	....	....	....	*l*	....	....	13	
n{230}	*n*	*n*	....	....	*n*	*n*	*n*	....	63	11–14, 21, 23–29.
j{450}	....	....	....	....	....	....	*j*	*j*	25	
m{110}	....	....	....	....	....	*m*	....	....	13	
h{430}	*h*	....	....	....	....	*h*	*h*	*h*	50	
k{210}	....	....	....	....	*k*	....	....	....	13	
p{111}	*p*	*p*	*p*	*p*	*p*	*p*	*p*	*p*	100	6, 7, 11–14, 21, 23–29.
r{322}	....	*r*	....	....	....	....	....	....	13	26.
s{533}	....	....	*s*	....	*s*	....	*s*	*s*	50	25, 28.
u{131}	....	....	....	....	....	....	*u*	....	13	28.
x{362}	....	....	....	....	....	....	*x*	....	13	28.

The common combinations observed on many crystals not measured are *a p*, *a n p*, *a b n p*, with occasional modifications due to rarer forms such as probably *h* and *s*.

ZONAL RELATIONS AND MARKINGS.

All the 13 forms of koechlinite lie in three zones, the prism zone, with *b l n j m h k a;* the pyramid zone *m p* with *m s r p;* and the pyramid zone *a x u*, as shown in figure 8. The three zones above named are all striated, and the intensity of the striation varies directly as the number of forms in that zone.

In addition to the regular striations there are markings of two other kinds on some of the crystals of koechlinite which deserve brief mention. Both kinds were observed under the microscope on the *a*{100} faces.

The surfaces of a few of the crystals are crowded with a mass of acute-angled markings, nearly equal in angle and nearly parallel. The acute points all face in one direction, as shown in the freehand sketch reproduced in figure 9. The symmetry of such markings indicates hemimorphism.

The markings of the second kind consist of straight lines, forming regular closed figures, one side of which is parallel to the vertical axis and the other side parallel to the intersection edge *a p* (shown in fig. 10). The vast majority of the lines parallel to the intersection edge *a p* are in one direction. In the drawing shown in

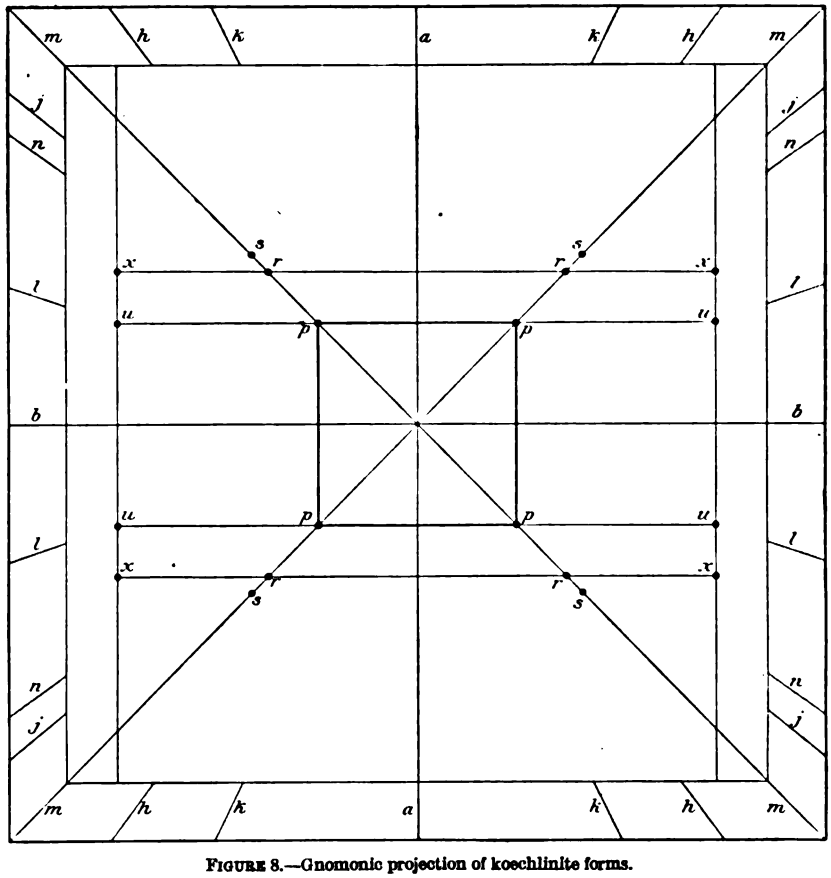


FIGURE 8.—Gnomonic projection of koechlinite forms.

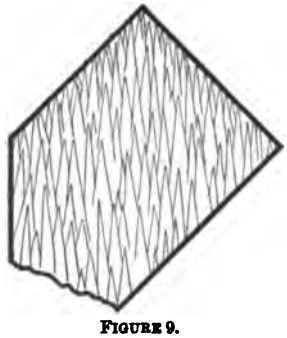


FIGURE 9.

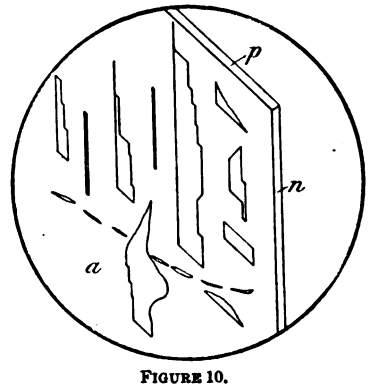


FIGURE 10.

FIGURE 9.—Acute-angled markings on $a\{100\}$, koechlinite.

FIGURE 10.—Regular markings on $a\{100\}$, koechlinite. Note excessive development of lines parallel to intersection $a(100)$–$p(111)$ over those parallel to intersection of $a(100)$–$p'(1\bar{1}1)$.

figure 10 only two of these lines are parallel to the edge (100)–(1$\bar{1}$1), whereas, as drawn, there are 31 lines parallel to the edge (100)–(111). The string of bubbles shown in the lower part of the figure are also approximately parallel to the edge (100)–(111). Such a preference to one of two supposedly equal directions naturally

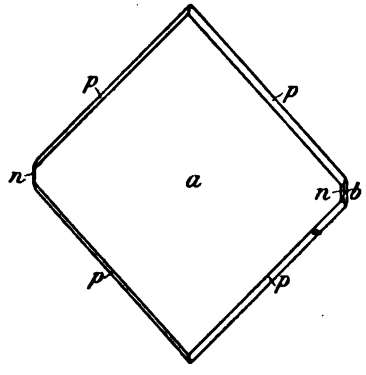


FIGURE 11.

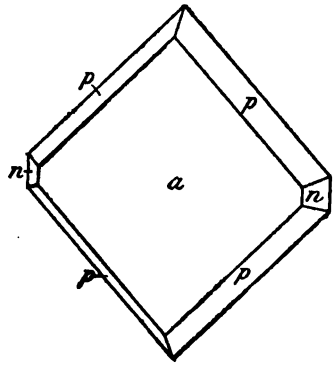


FIGURE 12.

FIGURE 11.—Square tabular habit of koechlinite (crystal 1). Forms: $a\{100\}$, $b\{010\}$, $n\{230\}$, $p\{111\}$.
FIGURE 12.—Stout tabular crystal of koechlinite. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

suggests hemimorphic development. The markings shown in figure 9 suggest hemimorphism in the direction of the vertical axis, whereas those shown in figure 10 suggest hemimorphism in the direction of the edge *a p*, which is inclined 45° to the vertical axis. The peculiarly distorted crystals (shown in fig. 7) in which the crystals are elongated parallel to one of the intersection edges of *a* and *p* also suggest the possibility of a hemimorphic development. Opposed to such an idea, however, are the holohedral distribution of the faces as determined on many crystals and the lack of conclusive evidence from the etch figures.

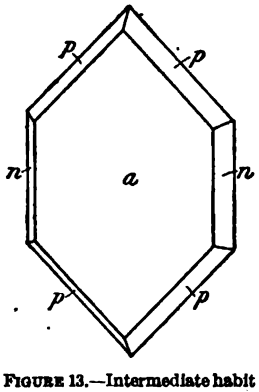


FIGURE 13.—Intermediate habit of koechlinite.

HABITS.

All the crystals of koechlinite are tabular in habit, but the thin tablets vary in shape from square ones to elongated ones, as already shown in figures 6 and 7.

The square tablets are very abundant and either consist of only the two forms $a\{100\}$ and $p\{111\}$ (see fig. 6, p. 14) or else have two of their edges modified by forms of the prism zone, as for example the first crystal measured, shown in figure 11.

A few crystals are not so thin as this one, and these slightly stouter crystals are also somewhat elongated parallel to the vertical axis. Such crystals were observed only under the microscope, but their

combination could be determined to be *a n p*, with possibly other forms present as line faces that would not modify the habit of the crystals. The approximate relative thickness and size of three such crystals, chosen to show the variation in habit, are reproduced in figures 12, 13, and 14.

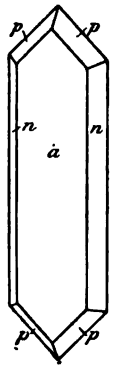


FIGURE 14.—Koechlinite crystal elongated parallel to the vertical axis.

Included in larger square crystals are a few small prismatic crystals which are an extreme example of elongation parallel to the vertical axis, as shown in figure 15. Such crystals were not observed by themselves, but as inclusions in larger ones they are not rare. They have a characteristic platy structure that was not seen on the individual short prismatic crystals (fig. 14). Figure 15 shows a sketch of a number of such minute prismatic crys-

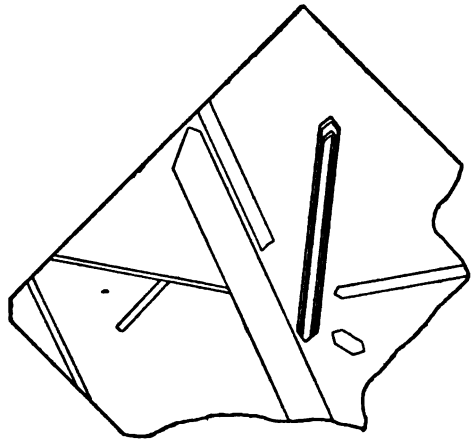


FIGURE 15.—Small prismatic crystals of koechlinite included in a larger square one.

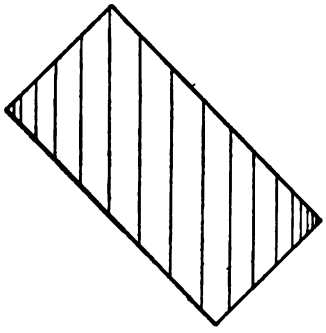


FIGURE 16.

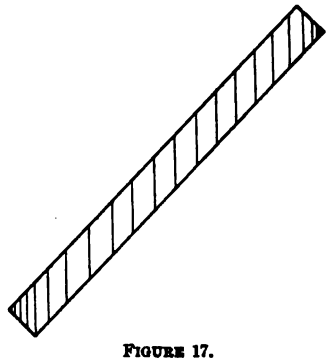


FIGURE 17.

FIGURE 16.—Common extent of elongation parallel to edge *a*(100) *p*(111) of crystal of koechlinite.
FIGURE 17.—Extreme case of distorted elongation parallel to edge *a p* noted on crystal of koechlinite.

tals included in a larger square one. Some of these included prismatic crystals may be in twin position, either to each other or to their larger host, but not all of them are thus regularly oriented.

Some of the tabular crystals are grouped together in parallel position and the individual crystals show neither exactly the same habit nor the same combination, although in general they are very similar. One such group, as it appeared under the microscope, is reproduced in figure 1 (p. 11). In this group the central crystal is decidedly elon-

gated parallel to the vertical axis, whereas the one on the right is nearly square.

In addition to the vertical extension of the prismatic crystals (figs. 13 and 14), the elongation parallel to one set of intersection edges of the unit pyramid *p* with the macropinacoid *a* is prominently developed. An example of such elongation has already been shown in figure 7 (p. 14), but the most abundant of such distortions occur where the elongation is about twice the width of the crystal, as shown in figure 16.

It is to be noted that contact twins of square habit will yield a crystal of similar shape to that shown in figure 16, but the difference in direction of the striations on *a*{100} at once differentiates these twin crystals (compare fig. 18) from the simple ones. The extreme observed distortion in a single crystal along the edge *a p* is shown in figure 17. The elongation of this crystal is 11 times its width.

TWINNING.

Twinning is common for koechlinite, and both contact and penetration twins occur. The twinning plane is the unit brachydome {011}, a form not observed on any of the crystals. By such twinning the faces of the macropinacoid *a* remain in the same plane, and as the angle (010) : (011) is 44° 56′, the angle between the twinned and untwinned adjacent faces of (011) is only 0° 08′, being thus so small as to be hardly detectable under the microscope. Consequently the different parts of a twin crystal extinguish so nearly the same that no difference can be seen under the microscope. In fact, in thin cleavage pieces a twin crystal can not be told from a simple one. On the thicker crystals a slight difference in shade of color, due to the pleochroism, can be noticed for the parts of a twin crystal. If the natural faces of *a*{100} are present, the striations on it at once furnish a satisfactory means of deciphering the twinning structure.

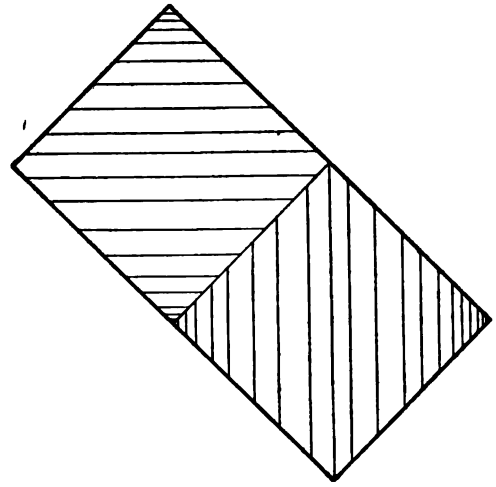


FIGURE 18.—Contact twin of koechlinite. Composition face is {011}. Compare figure 16.

In the contact twins the composition face is either {011} or {100}. If the twinning plane is the composition face, then the twinned crystal resembles in shape a simple crystal elongated parallel to the edge *a p* (as shown in fig. 16), but the difference in striations on *a*{100}

suffices to differentiate them. Twins in which the composition face is $a\{100\}$ are rare. These two varieties of contact twins are shown in figures 18 and 19.

By a repeated or synthetic twinning with {011} as composition face, a complex crystal may be built up. Figure 20 represents a cleavage piece of such a twinned koechlinite observed under the microscope. In the absence of the guiding striations on $a\{100\}$ it is impossible to determine whether this is a repeated twin with {011} as composition face or a simple crystal with cleavage or parting lines parallel to $p\{111\}$. As no such cleavage or parting lines have been found on the mineral, however, it is more reasonable to refer the observed structure to repeated twinning.

A symmetrically twinned fourling, with {011} as composition face, would yield a regular figure, in which the parts would only lack a few minutes of forming a theoretically closed solid, such as is shown in figure 21. This sketch explains the structure of the penetration twins described in the following para-

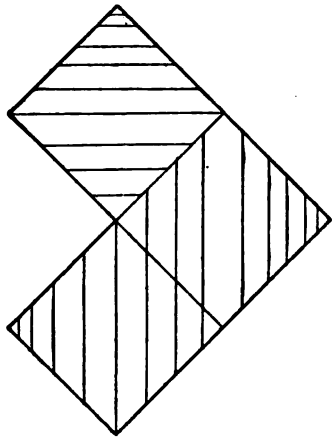


FIGURE 19.

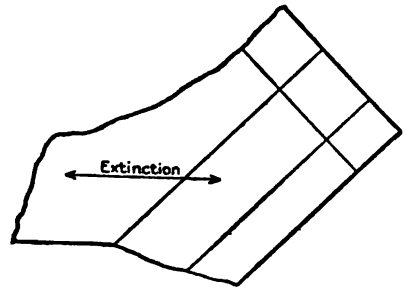


FIGURE 20.

FIGURE 19.—Contact twin of koechlinite. Composition face is $a\{100\}$.
FIGURE 20.—Cleavage piece of koechlinite, probably a polysynthetic twin with {011} as composition face.

graphs. An example of a twin, with {011} as composition face, is afforded by crystal 6, drawn in clinographic projection (fig. 29, p. 27).

Crystal 3 is an example of a crystal in which the two parts of a twin do not have the same combination. It is shown as it appeared under the microscope in figure 22.

The larger individual, elongated parallel to the edge a p, has the combination a p, whereas the smaller individual shows a prominent prism zone development. (Compare fig. 1, p. 11.)

The penetration twins are probably abundant, but unless the striated macropinacoid is present their detection is very difficult. Such a crystal, observed under the microscope, is shown in clinographic projection in figure 23.

A somewhat similar condition is presented by the imperfect crystal shown in figure 24 in orthographic projection on $a\{100\}$. The central part of the crystal (I) is in normal position, and III may

be considered as belonging to the untwinned central part (I). Part II, in twin position to I, lies between it and III. Part III may nevertheless be just as well considered as twinned to II, even though this brings it into parallel position with I. The crystal is thus similar to the one just described and illustrated in figure 23. By referring back to the theoretical twin shown in figure 21, it

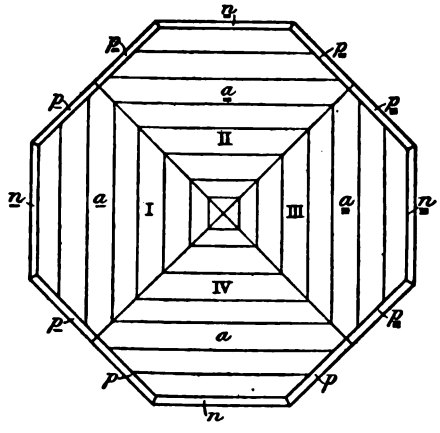


FIGURE 21.

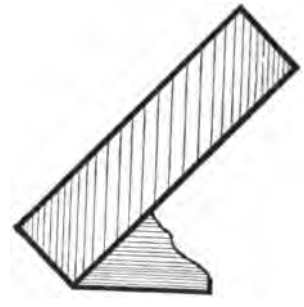


FIGURE 22.

FIGURE 21.—A theoretical fourling of koechlinite. Orthographic projection on $a\{100\}$. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

FIGURE 22.—Crystal 3, koechlinite. Contact twin with $\{011\}$ as composition face. The smaller individual has a different combination of forms from the larger one.

is seen that this can be interpreted in two ways. First I and III (fig. 21) may be considered as the same untwinned unit, to which II and IV (as one unit) are twinned. A preferable explanation, how-

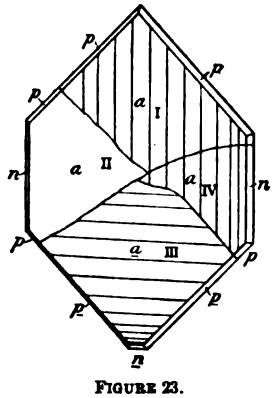


FIGURE 23.

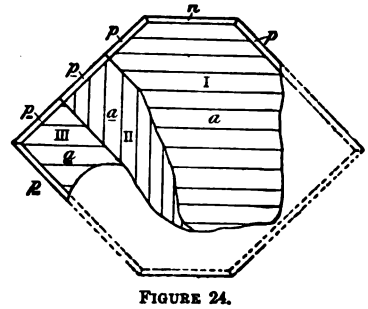


FIGURE 24.

FIGURE 23.—Clinographic projection of a penetration twin of koechlinite. The clear field (II) is free from striations, and its orientation is not known. The lower quadrant (III) is twinned on the upper one (I), and the remaining one (IV) may be considered as twinned on III, although it is in parallel position with the untwinned I. The continuity of the striations of I and IV would seem to indicate, however, that IV is not twinned but belongs inherently to I. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

FIGURE 24.—Orthographic projection on $a\{100\}$ of a penetration twin of koechlinite. Part II is twinned on I, and apparently III is twinned on II, yet III and I are in parallel position. Compare figure 23. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

ever, is that the drawing represents a fourling, in which I is twinned on IV, II on I, and III on II. A similar explanation is believed to hold for the crystals shown in figures 23 and 24.

MEASURED CRYSTALS.

Crystal 1, representing one of the square habit, with $a\{100\}$, $n\{230\}$, $b\{010\}$, and $p\{111\}$, is shown in figure 11 (p. 21). The form $h\{430\}$ is not shown in the drawing.

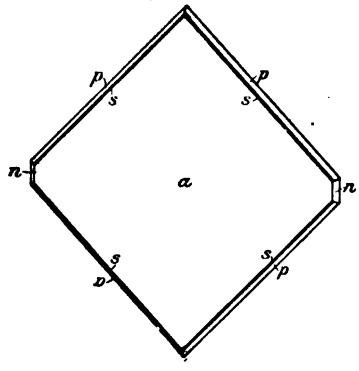


FIGURE 25.

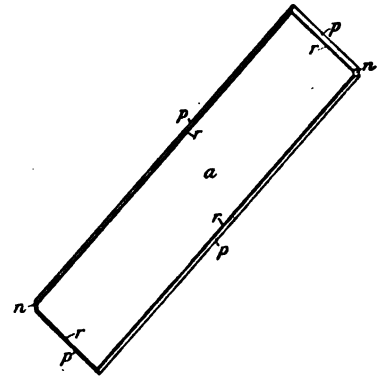


FIGURE 26.

FIGURE 25.—Crystal 5, koechlinite. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$, $s\{533\}$.
FIGURE 26.—Crystal 2, koechlinite. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$, $r\{322\}$.

Crystal 5 (fig. 25) represents one of similar habit, showing the line faces of $s\{533\}$. The rare prism $k\{210\}$, not shown in the figure, was observed only on this crystal.

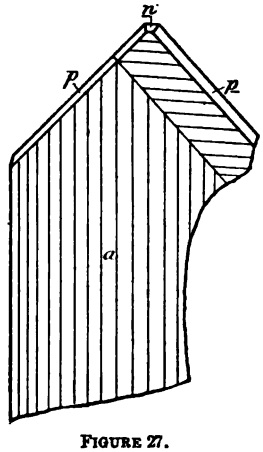


FIGURE 27.

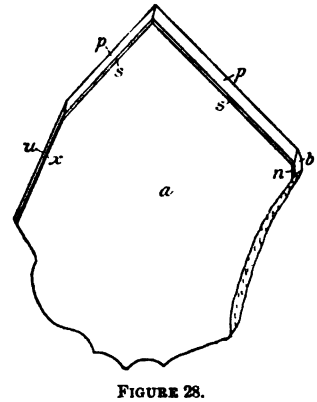


FIGURE 28.

FIGURE 27.—Crystal 4, koechlinite. Forms: $a\{100\}$, $p\{111\}$, $n\{230\}$.
FIGURE 28.—Crystal 7, koechlinite. Forms: $a\{100\}$, $b\{010\}$, $n\{230\}$, $p\{111\}$, $s\{533\}$, $u\{131\}$, $x\{362\}$.

Crystal 2 (fig. 26) is one of the distorted habit, elongated parallel to the edge a p. The pyramid $r\{322\}$ is present with $p\{111\}$.

Crystal 4 (fig. 27) is interesting as showing a twinned portion of the crystal with a face of $n\{230\}$ in the position of a macrodome.

The angle $a\{100\}$: $n\{230\}$ (54° 28′) is close to the angle $a\{100\}$: (203) (56° 10′).

Crystal 7 (fig. 28) is the only one on which the two pyramids $u\{131\}$ and $x\{362\}$ were definitely determined. In addition to the forms shown in the drawing, the two prisms $j\{450\}$ and $h\{430\}$ were observed on this crystal.

Crystal 6 is shown in orthographic projection on $a\{100\}$ in figure 29. The crystal is a well-developed contact twin with an irregular composition face, part of which appears to be $b\{010\}$ in the upper part of the drawing, but which is more likely rather irregular. In addition to the forms shown in figure 29, faces of $l\{130\}$, $m\{110\}$, and $\{430\}$ were determined on this crystal.

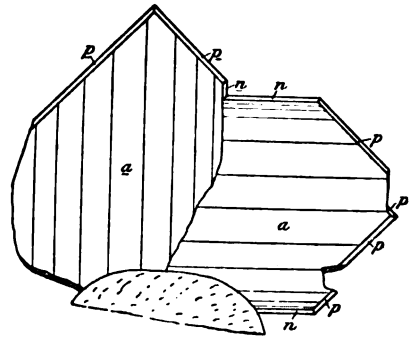


FIGURE 29.—Crystal 6, koechlinite. Orthographic projection on $a\{100\}$ of twin crystal. Forms: $a\{100\}$, $n\{230\}$, $p\{111\}$.

ETCH FIGURES.

The symmetry of the markings observed on some of the crystals, coupled with the prominent distortion along one set of intersection edges of a and p, strongly suggested a deviation from holohedral symmetry, and the concealing twinning might give the distribution of the faces an apparently higher grade of symmetry than the mineral in reality possessed. Recourse was therefore had to the effect of etching by dilute hydrochloric acid, and very interesting results were obtained, although the evidence is of an apparently conflicting nature and is thought not to justify decisive conclusions.

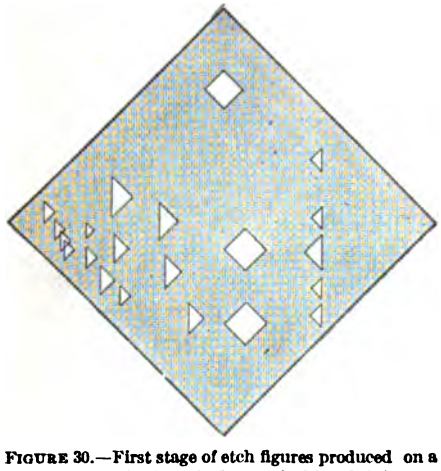


FIGURE 30.—First stage of etch figures produced on a symmetrically etched crystal of koechlinite.

Minute pits or etch figures are produced on the $a\{100\}$ faces of koechlinite in a few minutes when a crystal is immersed in cold dilute hydrochloric acid (about 1:5). If the acid is drained off and weaker

acid substituted the progress of the etching can be retarded and regulated. The effects produced can be readily studied by covering the crystal (on a glass slide) with a cover glass which, by its own weight, removes all but a film of solution from the *a* faces. The cover glass is then removed and fresh acid added to the crystal whenever it is desired to have the process of solution continue.

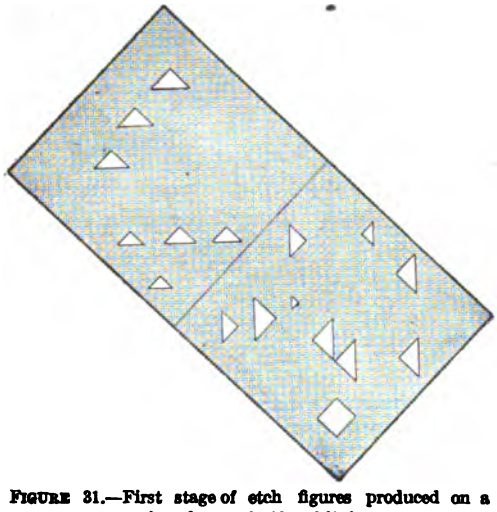


FIGURE 31.—First stage of etch figures produced on a winned crystal of koechlinite.

The process of solution of the crystal in hydrochloric acid, as observed, was not continuous, nor were the conditions constant, as the concentration of the acid, for example, was changed a number of times. It is not believed, however, that these interruptions are the cause of the apparent inconsistent facts observed.

The first etch figures produced are triangular and rectangular in shape. The triangular ones are symmetrical to a horizontal plane but not to a vertical plane. Moreover, some face to the right and others to the left. The rectangular figures may be conceived as a combination of right and left triangular ones. The distribution of these three kinds of figures does not necessarily bear any relation to the crystal itself. Each kind has been observed scattered over part of the entire crystal. An exceptionally symmetrically etched crystal is sketched in figure 30. As can readily be seen, the right-facing triangles are all on one side and the left-facing triangles are all on the other side. The rectangular figures, which may be built up of right and left triangles, occur only in the center.

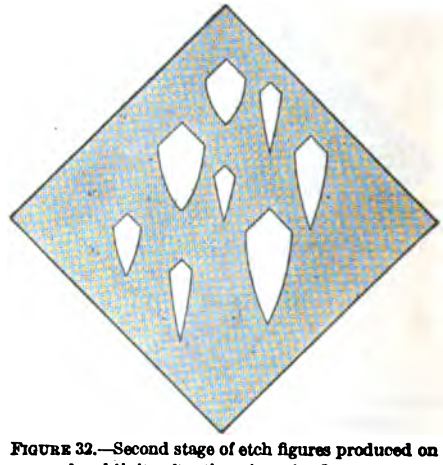


FIGURE 32.—Second stage of etch figures produced on koechlinite after the triangular figures.

A twin crystal shows similar etch figures, oriented in position with the twin part of the entire crystal, as shown in figure 31.

It is to be specially noted that these triangular etchings parallel with one another have an apparent hemimorphic symmetry in the direction of the *b* axis.

A little later etch figures are developed which, while hemimorphic in character, show this hemimorphism not in the direction of the *b* axis, like the triangular figures just described, but in the direction of the vertical or *c* axis. These etch figures are sketched in figure 32.

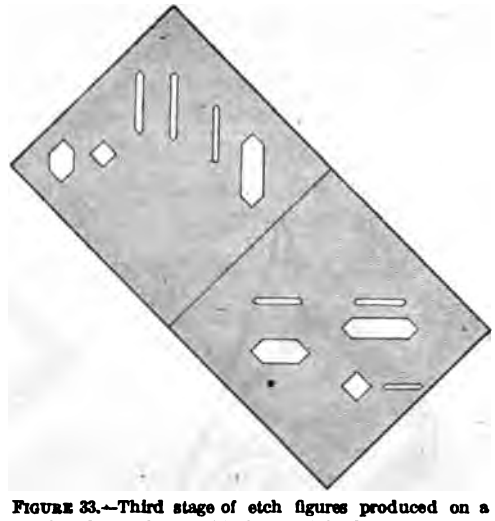


FIGURE 33.—Third stage of etch figures produced on a twinned crystal of koechlinite. All the figures now have holohedral symmetry.

At a still later period the triangular etch figures have all developed into rectangular ones and the vertically hemimorphic figures into hexagonal ones. They are shown in figure 33 as they were observed on a twin crystal. In a number of instances the gradual change in shape and symmetry from an original hemimorphic etch figure to the final rectangular or hexagonal one was continuously observed under the microscope, and the changes, as noted, are given in figure 34.

The final effect observed was most remarkable. The remnant of the crystal was bounded by sharply rectangular lines and its interior was full of similarly

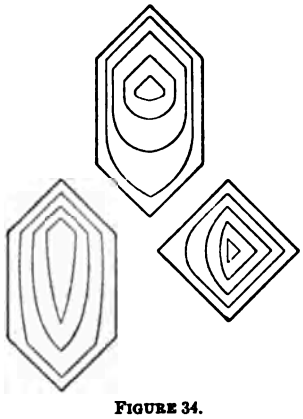


FIGURE 34.

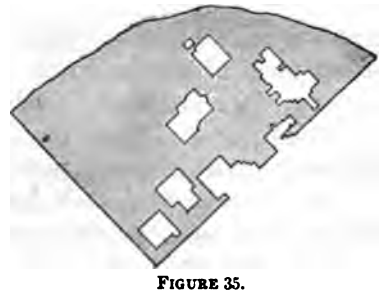


FIGURE 35.

FIGURE 34.—Last stage of etch figures produced on koechlinite. Change in shape and symmetry from figures with an original hemimorphic symmetry (inner outlines) to the final holohedral figures (outer outlines).

FIGURE 35.—Appearance of a corner of an etched and dissolving crystal of koechlinite.

sharply bounded rectangular holes, and the process of solution of the crystal continued in this way until the entire crystal was dissolved. The appearance of a corner of the crystal at a given moment is shown in figure 35.

The final etch figures developed on koechlinite by dilute hydrochloric acid are strictly holohedral in their symmetry, whereas those first produced are strongly hemimorphic. Is the symmetry of the figures first produced to be regarded as having no bearing on the symmetry of the mineral itself, or are the later holohedral etchings to be considered as twinned hemimorphic figures, thus ascribing to the mineral an intricate polysynthetic twinning? (See p. 21.)

The following observed facts seem to lend support to the idea of hemimorphic symmetry for koechlinite: The hemimorphic character of the markings observed on $a\{100\}$, the common distortion in un-

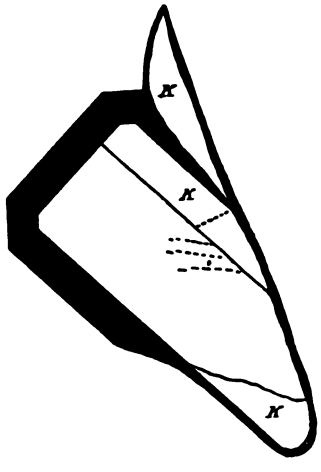


FIGURE 36.

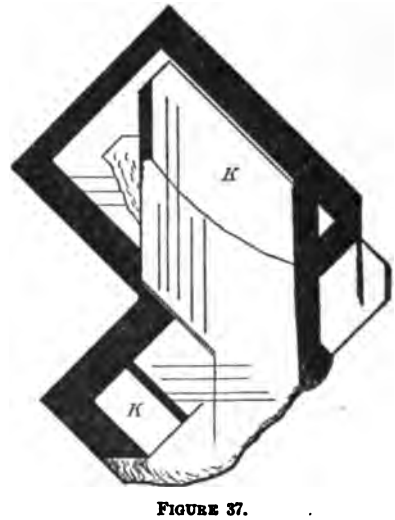


FIGURE 37.

FIGURE 36.—Intergrowth of unknown mineral C with koechlinite. The areas occupied by koechlinite are marked *K*.

FIGURE 37.—Intergrowth of unknown mineral C with koechlinite (*K*).

twinned crystals along one pair of edges *a p;* the unequal size of the different faces of a form on the same crystal; and the hemimorphic symmetry of the artificially produced etch figures, as shown in figures 30, 31, and 32.

Opposed to the idea of hemimorphic symmetry of the crystals are the facts that the final etch figures are strictly holohedral in their symmetry and that the distribution of faces on the crystals favors holohedral symmetry, although it must be said that the measured crystals were not developed perfectly enough nor were the terminal faces sufficiently large to warrant a definite conclusion.

INTERGROWTHS.

Intergrowths of koechlinite with the colorless mineral described on page 13 as unknown mineral C were observed several times. The two minerals are, so far as the observations go, in parallel untwinned position, the striations being parallel. The contact line is straight in some intergrowths and very irregular in others. In the typical example of an intergrowth shown in figure 36 the main mass of the crystal consists of the colorless unknown mineral C and there are three smaller portions of koechlinite.

In the best developed example of this intergrowth, reproduced in figure 37, the main mass of the crystal consists of unknown mineral C twinned, and each twin portion contains intergrown koechlinite.

RELATION TO OTHER MINERALS.

There are no known minerals with which koechlinite shows a close analogy in type of chemical formula. The mineral jeremejevite has the formula $Al_2O_3.B_2O_3$, which, in type, conforms to the formula of koechlinite, but jeremejevite is hexagonal, although the so-called eichwaldite, intergrown with jeremejevite, has been interpreted as orthorhombic, with axes which, if doubled, are not far from those of koechlinite:

Eichwaldite, $2a:b:2c=1.1046:1:1.0868$.
Koechlinite, $a:b:c=0.9774:1:1.0026$.

A number of hydrous minerals are analogous to koechlinite in composition except for the water, but crystallographically they seem to show no close relation to koechlinite. These hydrous minerals are listed below.

Koechlinite	$Bi_2O_3.MoO_3$	Orthorhombic.
Montanite	$Bi_2O_3.TeO_3.2H_2O$.	
Ferritungstite	$Fe_2O_3.WO_3.6H_2O$	Hexagonal.
Utahite	$Fe_2O_3.SO_3.\frac{4}{3}H_2O$?	Hexagonal.
Planoferrite	$Fe_2O_3.SO_3.15H_2O$	Orthorhombic.
Aluminite	$Al_2O_3.SO_3.9H_2O$.	

Attention may be called to a furnace product which in composition is similar in type to koechlinite but of which unfortunately few crystallographic data seem to be available. This is a crystalline compound described by Pearce [1] and having, according to his analysis, the composition expressed by the formula $As_2O_3.SO_3$. The crystallographic data are too meager to warrant any conclusion as to the relation of the compound to koechlinite. Pearce describes it as follows:

The usual condition of the material was small spear-shaped crystals of a pearly luster. * * * These crystals were in many cases more than 1 inch in size and

[1] Pearce, Richard, On a remarkable crystalline compound of arsenious and sulphuric acids: Colorado Sci. Soc. Proc., vol. 3, p. 255, 1888-1890.

beautifully modified. The form will, in all probability, be found to be monoclinic. They are semitransparent to transparent; color, white; cleavage, perfect; luster, somewhat pearly and adamantine.

PHYSICAL PROPERTIES.

The cleavage of koechlinite is perfect parallel to the macropinacoid $a\{100\}$. A second imperfect cleavage seems to exist after some other form in the prism zone. The crystals are very brittle, breaking readily under the slighest pressure. The extreme thinness of most of the crystals naturally increases their tendency to break. The hardness and density are not known.

OPTICAL PROPERTIES.

The body color of the crystals is greenish yellow and corresponds to "oil-yellow" on Plate V of Ridgway's "Color standards.."[1] When heated but not fused the greenish-yellow crystals become brown, but on cooling they revert to their original color. The fused mineral becomes dark brown and on cooling suddenly changes to a very pale yellow which becomes white when cold. The luster is vitreous, slightly adamantine. The streak is pale greenish yellow. The crystals are transparent, the transmitted color being greenish yellow, like the body color.

A bisectrix emerges normal to the macropinacoid, and the trace of the axial plane is normal to the striations and therefore parallel to $c\{001\}$. The axial angle seen on $a\{100\}$ is very large and the obtuse bisectrix probably emerges normal to $a\{100\}$. On this assumption the orientation of the mineral is as follows:

$$a \text{ axis} = Z$$
$$b \text{ axis} = X$$
$$c \text{ axis} = Y$$

If the a axis is the direction of the obtuse bisectrix, then the mineral is negative.

The refractive indices are very high. Mr. Esper S. Larsen kindly determined the index by the embedding method[2] and found $\beta_{Li} = 2.55$ with an estimated birefringence of about 0.1.

The crystals have a very slight pleochroism, observable only on the thicker ones. As observed on $a\{100\}$, the mineral is not pleochroic, except that on the thicker crystals the color is slightly deeper normal to the striations than parallel to the striations.

[1] Ridgway, Robert, Color standards and color nomenclature, Washington, 1912.

[2] Merwin, H. E., and Larsen, E. S., Mixtures of amorphous sulphur and selenium as immersion media for the determination of high refractive indices with the microscope: Am. Jour. Sci., 4th ser., vol. 34, p. 42, 1912.

CHEMICAL PROPERTIES.

PYROGNOSTICS.

The mineral fuses readily in a closed tube without giving off water or any sublimate. The color changes are described on page 32. The crystals dissolve readily in HCl but not so readily in HNO_3. The deep-blue color of a lower oxide of molybdenum is readily obtained by heating the mineral with concentrated H_2SO_4 and evaporating nearly to dryness in a white porcelain crucible. The bismuth iodide sublimate on charcoal is strong and characteristic.

QUANTITATIVE COMPOSITION.

The material analyzed was nearly free from inclusions except for admixed quartz. The three unknown minerals already described were present in only minute amounts in the samples analyzed, as the crystals of koechlinite were separately picked out of the material removed from the cavities. The mineral was at first taken to be Bi_2O_3, and as the first analysis totaled only 78.2 per cent, it was thought that a mistake had been made in the determination of bismuth. On a second sample a determination of bismuth gave the same result. As each analysis totaled less than 100 per cent, it was evident that an unrecognized constituent was present. Nearly all the remaining material was sacrificed in the determination of this unknown constituent, which was finally identified as molybdenum. Another specimen of the mineral had then to be utilized to obtain material for a quantitative determination of the molybdenum. The absence of the common bases and of any sulphate, phosphate, carbonate, borate, or tungstate radicle was qualitatively determined. The results obtained are shown below.

Analyses of koechlinite.

	1	2	3
Weight of sample.....gram..	0.0925	0.1003	0.0424
Bi_2O_3.....	73.0	51.6	71.9
MoO_3.....	Not det.	Not det.	21.2
H_2O (loss on ignition).....	.2	.....	.....
Quartz.....	5.0	34.1	5.4
	78.2	85.7	98.5

The results are restated below with the admixed quartz deducted, being thus reduced to a comparative basis.

Analyses and ratio of koechlinite with quartz deducted.

	1	2	3	Average.	Ratio.	Calculated.
Bi_2O_3	76.8	78.3	76.1	77.1	0.166 or 1.00	76.36
MoO_3	.....	.....	22.4	22.4	.155 or .93	23.64
H_2O	.2	.....	.....	.2	.....	.....
	77.0	78.3	98.5	99.7	.....	100.00

The ratio obtained leads to the formula $Bi_2O_3.MoO_3$, which can be interpreted as bismuthyl molybdate $(BiO)'_3.MoO_4$.

DIAGNOSTIC PROPERTIES.

The rectangular crystals with diagonal striations, and particularly the elongated distorted crystals, are very characteristic of koechlinite. The absence of water and a qualitative determination of bismuth and molybdenum on such crystals would positively identify koechlinite.

INYOITE AND MEYERHOFFERITE, TWO NEW CALCIUM BORATES.

RELATION OF MEYERHOFFERITE TO INYOITE.

Two specimens of large crystals having a rhombic shape were collected by Hoyt S. Gale, of the United States Geological Survey, in the Death Valley region of California. The fact that the mineral was a borate was determined, but its specific relation could not be fixed. As a preliminary examination failed to identify the specimens with any known mineral, they were delivered to the writer, who would here express his gratitude to Mr. Gale for his kindness in allowing the free use and description of the material.

The large crystals, whose rhombic shape could not be correlated with that of any known borate mineral, are opaque and covered with small shining transparent colorless prismatic crystals. A broken surface of the rhombic crystals shows a peculiar reticulated structure formed by a white silky fibrous material. The inner structure of the large crystals, as revealed on the broken surfaces, indicated that a change had taken place and that the material now forming the crystals was different from that of which they were originally composed. The chemical investigation has confirmed this inference. When one of the large crystals was broken up a nucleus of fresh, unaltered glassy material was found in its center. By alteration this glassy material has changed into the silky fibrous material that now forms the bulk of the specimens.

The investigation has shown that both parts of the specimen are mineralogically new and that two distinct mineral species are present. The glassy material, of which the large rhombic crystals were originally formed, is here named inyoite. It is a hydrous calcium borate having the formula $2CaO.3B_2O_3.13H_2O$. Inyoite alters to a similar hydrous calcium borate with only seven molecules of water, which is here called meyerhofferite. The silky fibrous masses and the shining transparent prisms are but two different forms of meyerhofferite. Inyoite is therefore the parent mineral which has altered to an aggregate of fibrous and prismatic crystals of secondary meyerhofferite.

The two specimens are shown in Plate I and the forms of the secondary meyerhofferite are shown in Plate II.

NOMENCLATURE.

The name inyoite is derived from the locality where the specimens were found—Inyo County, Cal. The second of the new borates is named meyerhofferite after Wilhelm Meyerhoffer, who with J. H.

van't Hoff worked for many years on the composition of the saline minerals and so about 1906 came to study the calcium borates. His death occurred soon after he began his investigation of these borates and it seems that one of the very last of the salts studied by him was the compound $2CaO.3B_2O_3.7H_2O$. Now that this compound has been found in nature as a mineral, it is appropriately named after him.

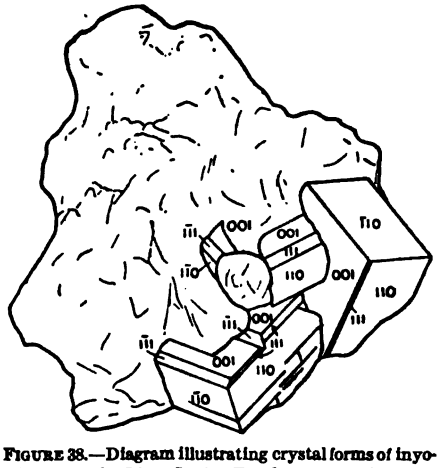


FIGURE 38.—Diagram illustrating crystal forms of inyoite shown in Plate I, *A*. The large crystal on the right was broken up, and glassy unaltered inyoite was obtained from its center. Nearly the entire specimen has altered to meyerhofferite.

LOCALITY AND PARAGENESIS.

The exact locality from which the specimens were obtained is a prospect tunnel in the Mount Blanco district, on Furnace Creek, near Death Valley, Inyo County, Cal. The following notes on the occurrence of the minerals have been supplied by Mr. Gale. The tunnel was referred to by Mr. Corkill, in charge of developments on the property, as the "jewelry shop," because of the display of beautifully crystalline colemanite throughout the greater part of its length. The tunnel had penetrated what Mr. Gale considered to be vein material in a rather unusual crystalline form. The glassy colemanite lay as if crystallized in large geodes formed of broad horizontally disposed cavities lined with coarsely drusy botryoidal bunches, the surfaces of which were completely covered with transparent crystals, with sharp edges and corners. In the light of the candles used to examine the tunnel the reflections from the myriads of minute sparkling crystal faces made a very brilliant display.

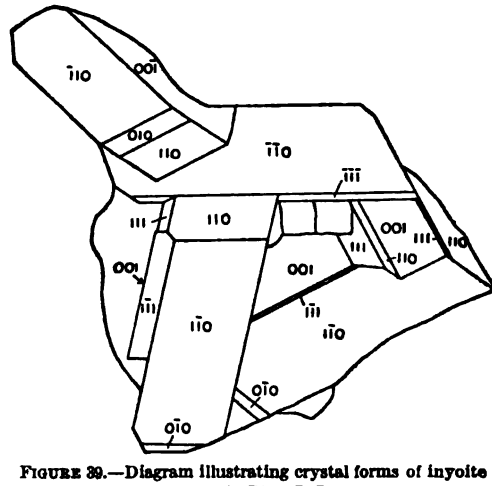
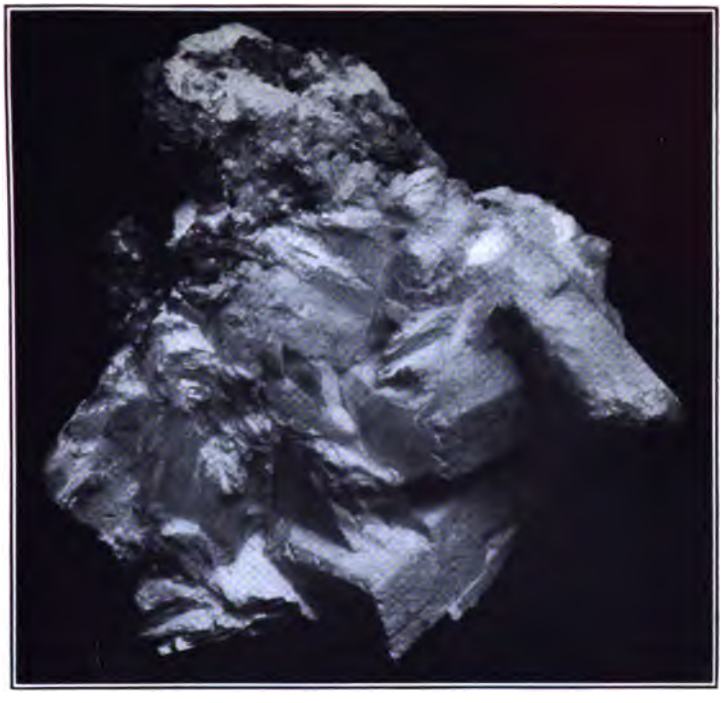


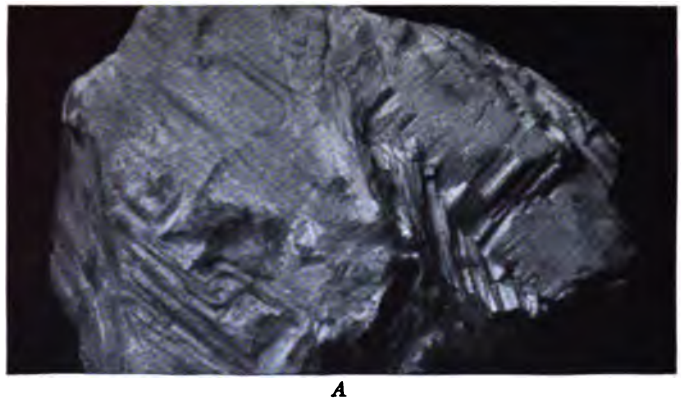
FIGURE 39.—Diagram illustrating crystal forms of inyoite shown in Plate I, *B*.

The two new minerals, inyoite and meyerhofferite, were directly associated with this colemanite, the particular specimens collected having been pried off in the geode-like cavities.

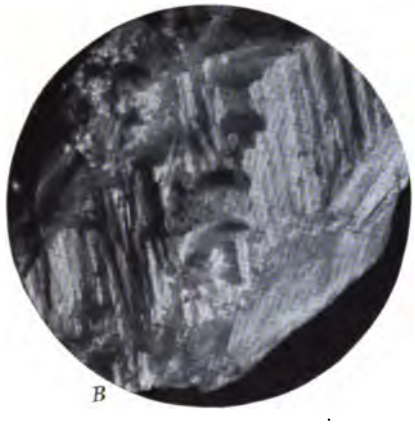


A. CRYSTALS OF INYOITE ON MASSIVE MINERAL, NATURAL SIZE.

B. GROUP OF CRYSTALS OF INYOITE, ENLARGED 2 DIAMETERS.

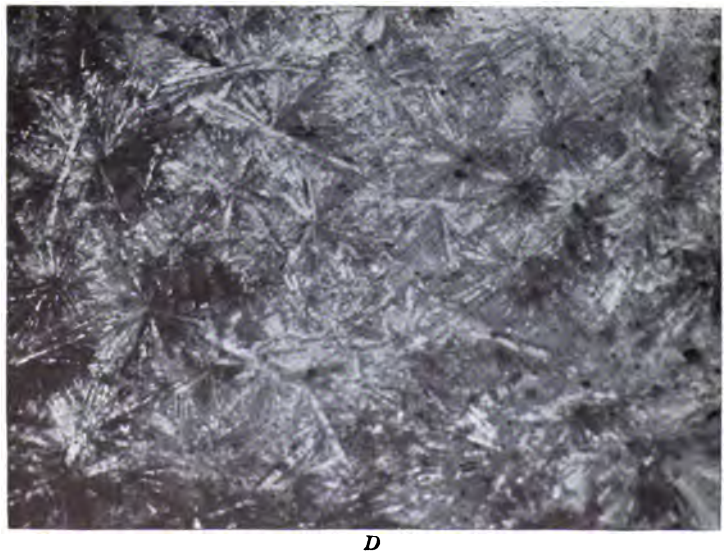


A



B

C



D

ALTERATION OF INYOITE TO MEYERHOFFERITE.

A, B, C. Reticulated structure of altered inyoite. Enlarged 2⅘ diameters. *D.* Stellate groups of crystals of meyerhofferite on the surface of cyrstals of inyoite. Enlarged about 7 diameters.

The new minerals are probably of similar origin to the colemanite, which is apparently an open-space vein filling, the deposit being in fissures cutting shales and sandstones composed largely of tuffaceous material, variously referred to in California and Nevada under the terms Rosamond series, Esmeralda series, and Siebert "lake beds." The veins are closely associated with interbedded volcanic flows, which consist of vesicular and locally amygdaloidal basalt, also with dikes of similar composition.

The colemanite from these deposits has not yet been mined commercially, and all the properties are still in the prospect stage. The Mount Blanco deposit has, however, often been referred to as the largest in the United States. Besides colemanite, it contains a very considerable quantity of pandermite. It is said that ulexite found in the surface soils of the hills below the colemanite vein was originally scraped and worked for borax along with the ulexite deposits in the valley.

INYOITE.

CRYSTALLOGRAPHY.

GENERAL CHARACTER OF CRYSTALS.

The large crystals of inyoite, as shown in Plate I, are so grown together that only a few angles could be measured on each crystal. Moreover, the alteration to meyerhofferite, particularly the development of stellate groups of prismatic crystals on the surfaces of the original inyoite crystals, as shown in Plate II, *D*, makes it difficult to obtain good measurements. A further trouble was found in that the only pyramidal form observed on inyoite was narrow and became considerably uneven and rounded by the alteration. The discovery of better crystals of inyoite, especially if unaltered, would necessitate a revision of the crystallographic data here presented.

Six crystals which afforded the most suitable material for measurement were utilized. The crystals are all simple and had the same general rhombic habit, as shown in Plate I and figure 40 (p. 38).

CALCULATION OF ELEMENTS.

The crystals are monoclinic, and the elements were calculated from the average of the following measurements made with a simple contact goniometer:

Measurements of angles of inyoite.

Angle.	1	2	3	4	5	6	Average.
(001):(110)	68°, 67°, 68°	71°, 70°	.....	.....	.....	72°	69° 20′
(110):(1$\bar{1}$0)	80°	79°	.....	80°	80°	.....	79° 45′
(110):(111)	35°	35°	38°	.....	37°	.....	36° 15′
(010):(001)	.....	.....	91°	.....	.....	.....	.....

From the three fundamental angles given, namely, (001) : (110) = 69° 20′, (110) : (1$\bar{1}$0) = 79° 45′, and (110) : (111) = 36° 15′, the axial elements were calculated and found to be as follows:

$$a : b : c = 0.9408 : 1 : 0.6665;\ \beta = 62° 37'.$$

FORMS.

The total number of forms observed is four, as follows:

Pinacoids: $c\{001\}$, $b\{010\}$.
Prism: $m\{110\}$.
Pyramid: $p\{111\}$.

The basal pinacoid $c\{001\}$ is the dominant form and the crystals are tabular parallel to this form. (Compare fig. 40.) It is also a direction of cleavage. The brachypinacoid is small and the least prominent form. It was observed on about half the crystals examined. The unit prism is medium in size and approximately one-third as large as the base. The unit pyramid varies in size, even on the same crystal, but is always much smaller than the prism.

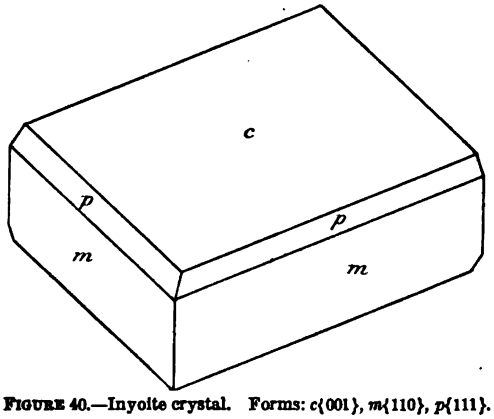


FIGURE 40.—Inyoite crystal. Forms: $c\{001\}$, $m\{110\}$, $p\{111\}$.

The relative size of the different forms and the general tabular habit are shown in figure 40.

PHYSICAL PROPERTIES.

The cleavage of inyoite is good parallel to the basal pinacoid $c\{001\}$. The lower crystal of the group shown in Plate I, *A*, shows this cleavage, and so do the fresh pieces of inyoite found in the interior of the large crystals. The fracture is irregular, and the mineral is brittle. The hardness is about 2. The density, determined by means of Thoulet solution, is 1.875.

OPTICAL PROPERTIES.

The fresh inyoite is glassy and colorless; the altered material (meyerhofferite) is white. The luster is vitreous, and the mineral is transparent, although the progressing alteration soon clouds the fresh mineral, making it opaque.

The optical orientation could not be determined, as the fresh pieces found in the interior of the large altered crystals showed no crystal boundaries. Cleavage pieces, parallel to the basal pinacoid,

showed the emergence of an inclined bisectrix. The axial angle is large and negative. The angle $2E$ for sodium light was measured as 118°. No change in this result could be observed for lithium or thallium light. Numerous markings on the base are nearly rectangular, having measured angles between 80° and 90°. These markings are apparently parallel to the unit prism and may represent the traces of an imperfect prismatic cleavage. On the assumption that the orientation of these markings on the basal cleavage is correct, the optical orientation of inyoite can be stated as follows: Axial plane parallel to $b\{010\}$; acute negative bisectrix obliquely emergent on $c\{001\}$.

The refractive indices were kindly measured by the immersion method by Mr. Esper S. Larsen, who obtained the following results:

$$\alpha=1.495. \quad \beta=1.51. \quad \gamma=1.520. \quad (\gamma-\alpha)=0.025.$$

CHEMICAL PROPERTIES.

PYROGNOSTICS.

Heated before the blowpipe, the mineral decrepitates and fuses with much intumescence, giving a greenish boron flame. When it is heated in a closed tube abundant water is readily given off. The mineral is easily soluble in acids.

QUANTITATIVE COMPOSITION.

The transparent glassy material was free from any inclusions of other minerals, and the sample analyzed was free from adhering meyerhofferite. The total available amount of unaltered inyoite was very small, and for the analysis only 0.1037 gram could be obtained. The boric acid was not determined, and qualitative tests showed the absence of silica, alumina, magnesia, alkalies, phosphate, sulphate, carbonate, etc. The analysis and ratios deduced therefrom are as follows:

Analysis and ratios of inyoite.

	Analysis.	Ratios.	Calculated.
CaO	20.5	0.366 or 2.02 or 2×1.01	20.2
B_2O_3	[37.2]	.531 or 2.93 or 3× .98	37.8
H_2O below 110°	26.1	1.450 or 8.01 or 8×1.00	25.9
H_2O above 110°	16.2	.900 or 4.97 or 5× .99	16.1
	100.0		100.0

The ratios conform closely to the numbers 2 : 3 : 8 : 5, giving the formula $2CaO.3B_2O_3.13H_2O$. Of the water $\frac{8}{13}$ goes off below 110°, so that in the conventional way the formula may be written $2CaO.3B_2O_3.5H_2O+8H_2O$.

ALTERATION.

The specimens shown in Plate I were very largely altered when collected and should perhaps be called "meyerhofferite pseudomorph after inyoite," rather than inyoite. The alteration to meyerhofferite has changed the large rhombic crystals of the inyoite from a colorless transparent and glassy material to a compact aggregate of white, opaque, silky fibers. These fibers are arranged either in irregular masses, in radiating groups, or more commonly and characteristically in parallel oriented groups, which for the most part form a rectangular network, such as is shown in Plate II, *A*, *B*, and *C*. In this network are areas of parallel fibers which lie at an angle of about 45° to the rectangular ones, as is well shown in Plate II, *A*. Most of these fibers are silky white and opaque, although embedded in them are numerous transparent glassy prisms of the same material. The lower portion of the specimen shown in Plate I, *A*, is similarly composed of these compact fibers of meyerhofferite.

It would be a most interesting study to trace the orientation of the individual meyerhofferite crystals, both with regard to the reticulated structure of the entire mass as well as to the original inyoite crystals, but such a study could not be undertaken for lack of time.

A second mode of occurrence of the meyerhofferite crystals is as stellate groups on the surface of the large crystals of altered inyoite. These radiating clusters appear both singly and in groups, and a particularly rich and well-developed cluster is shown enlarged in Plate II, *D*. These prismatic meyerhofferite crystals are transparent and glassy. It was at first thought that the opaque, white, silky, fibrous crystals were different from the transparent, colorless glassy prisms, but they have been proved to be identical.

Meyerhofferite contains less water than inyoite, and it might be expected that the crystals would show a further loss of water on long exposure to the air, but no such loss has been observed. Under the conditions which existed at the place of formation of the specimens meyerhofferite seems to be the stable compound

DIAGNOSTIC PROPERTIES.

The rhombic shape of the large crystals, now altered to a fibrous aggregate of white and colorless prisms, and the low refractive index of the mineral (1.5) serve to distinguish inyoite from the other known borates.

MEYERHOFFERITE.

CRYSTALLOGRAPHY.

GENERAL CHARACTER OF CRYSTALS.

The 21 crystals measured averaged about 2 to 3 millimeters in length and about 0.3 to 0.5 millimeter in thickness. Crystals 1 millimeter thick and 1 centimeter long are not rare. All the crystals examined are prismatic in habit. No twins were detected.

CALCULATION OF ELEMENTS.

The triclinic crystals were measured by the two-circle goniometer, the prismatic habit rendering it very easy to adjust the crystals in polar position. The excellent clinopinacoidal cleavage was usually developed enough to give a good reflection, and its measurement, aided by the readings on the other faces of the prism zone, gave good results for v_0. The few forms whose measurements could be used for a calculation of the elements were as follows: $a\{100\}$, $m\{110\}$, $M\{1\bar{1}0\}$, $t\{101\}$, $y\{\bar{1}01\}$, $p\{111\}$. The measurements of these six forms yielded nine angles, of which only five are necessary. The method of two-circle measurement allows the use of all the available angles, and all nine were therefore used, the final results being a better average of all the measurements than could be obtained by the arbitrary selection of only five angles.

Details of the method of calculation are given in the publications of Borgström and Goldschmidt[1] and of Moses and Rogers.[2]

The angles of $t\{101\}$, $y\{\bar{1}01\}$, and $p\{111\}$ were used for obtaining an average value for x'_0, and $p'_0 \sin v$, from which, as v is known ($=\phi(100)$), p'_0 is readily calculated. An independent value of v is also obtained from the values of $t\{101\}$ and $p\{111\}$. Values for y'_0 are obtained from $t\{101\}$, $y\{\bar{1}01\}$ and $p\{111\}$ and for q'_0 from $p\{111\}$. Independently from the terminal forms, v and $\frac{p'_0}{q'_0}$ are calculated from the measurements of the prisms $m\{110\}$ and $M\{1\bar{1}0\}$. By taking the value found for p'_0 from the terminal faces, a second value for q'_0 can be found from the ratio of $\frac{p'_0}{q'_0}$, obtained from the prisms.

The averages of the measured angles of the six forms used are as follows, and from these figures average values for the crystallographic elements are calculated.[3]

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[1] Borgström, L., and Goldschmidt, V., Krystallberechnung im triklinen System illustriert am Anorthit: Zeitschr. Kryst. Min., vol. 41, p. 63, 1905.

[2] Moses, A. J., and Rogers, A. F., Formulæ and graphic methods for determining crystals in terms of coordinate angles and Miller indexes: School of Mines Quart., vol. 24, p. 1, 1902.

[3] The writer wishes to express his gratitude to Prof. Victor Goldschmidt, of Heidelberg, who kindly verified the crystallographic calculations of meyerhofferite.

Averages of measured angles of meyerhofferite.

Form.	Number of measurements.	ϕ		ρ	
		°	′	°	′
$a\{100\}$	26	93	12	90	00
$m\{110\}$	19	54	15	90	00
$M\{1\bar{1}0\}$	13	129	49	90	00
$t\{101\}$	9	94	01	38	35
$y\{\bar{1}01\}$	8	87	00	50	22
$p\{111\}$	9	47	34	46	54

The values obtained are as follows:

$x'_0=-0.2049$ from $t\{101\}$ and $y\{\bar{1}01\}$.
$x'_0=-0.2085$ from $y\{\bar{1}01\}$ and $p\{111\}$.
$y'_0=0.0036$ from $t\{101\}$ and $y\{\bar{1}01\}$.
$p'_0=1.0005$ from $t\{101\}$, $y\{\bar{1}01\}$, and $p\{111\}$.
$q'_0=0.7769$ from $p\{111\}$.
$q'_0=0.7761$ from value of p'_0 and $\frac{p'_0}{q'_0}$ (prisms).
$\frac{p'_0}{q'_0}=1.2940$ from $t\{101\}$, $y\{\bar{1}01\}$, and $p\{111\}$.
$\frac{p'_0}{q'_0}=1.2870$ from $m\{110\}$ and $M\{1\bar{1}0\}$.
$v=93° 12'$ from $a\{100\}$.
$v=93° 14'$ from $m\{110\}$ and $M\{1\bar{1}0\}$.

The elements obtained from the average of these values, with their proper weights, are shown in the following table. The figures given were not obtained by arbitrarily assuming certain values as correct, but by averaging all the available results obtained directly from the measurements. It will be found, therefore, that the angles calculated from these elements are not the same as those with which the determinations originally started but vary slightly therefrom.

Axial elements of meyerhofferite.

Projection elements.	Polar elements.	Linear elements.
$x'_0=-0.2067$	$p_0=0.9798$	$a_0=1.0222$
$y'_0=0.0036$	$q_0=0.7602$	$b_0=1.2902$
$p'_0=1.0005$	$r_0=1$	$c_0=1$
$q'_0=0.7763$	$\lambda=89° 48'$	$a=0.7923$
$v=93° 13'$	$\mu=101° 41'$	$b=1.0000$
$h=1$	$v=93° 13'$	$c=0.7750$
	$x_0=-0.2024$	$\alpha=89° 32'$
	$y_0=0.0036$	$\beta=78° 19'$
		$\gamma=86° 52'$

On a gnomonic projection carefully plotted directly from the measurements the elements could be read off and showed a close agreement with the calculated results.

Comparison of calculated and graphic values.

	Calculated.	Measured on gnomonic projection.
x'_0	−0.2067	−0.206
y'_0	.0036	.005
p'_0	1.0005	1.01
q'_0	.7763	.772
v	93° 13′	93° 30′

The measurements from which these averages are obtained are as follows:

Measurements of a{100}, meyerhofferite.

Crystal No.	Reflection.	Size of face.	φ °	φ ′	Crystal No.	Reflection.	Size of face.	φ °	φ ′
1	Good	Large[a]	93	10	15	Fair	Large	[d]93	45
1	Good	Large[a]	93	18	16	Fair	Large[c]	93	09
2	Good	Large	93	06	16	Poor	Large	93	17
2	Poor	Large	93	11	17	Fair	Large[c]	93	11
4	Excellent	Small[a]	[b]93	34	17	Excellent	Medium	93	11
6	Fair	Large	93	15	18	Fair	Medium[c]	93	17
7	Fair	Large	93	06	18	Fair	Large[c]	93	10
7	Poor	Large	93	07	19	Good	Medium	93	03
9	Fair	Large[c]	93	03	20	Good	Large	93	12
9	Fair	Large	92	48	21	Poor	Line face	93	13
10	Good	Large[c]	[b]93	40	21	Poor	Line face	93	09
10	Fair	Large[c]	93	17					
11	Fair	Large[c]	[d]93	41	Average of 26 measurements			93	12
12	Fair	Large[c]	[d]93	45	Average of good and excellent reflections			93	16½
13	Good	Large	93	14					
13	Fair	Large	93	32	Average of fair reflections			93	09
14	Good	Large	93	17	Average of poor reflections			93	11
14	Fair	Medium	92	48	Calculated			93	13
15	Poor	Large	[d]93	36					

[a] Cleavage (?) face.
[b] High, but included because of good reflection.
[c] Striated face.
[d] Excluded from average.

Measurements of t{101}, meyerhofferite.

Crystal No.	Reflection.	Size of face.	φ °	φ ′	ρ °	ρ ′
6	Poor	Minute	[a]90	04	39	00
9	Poor	Narrow	93	56	38	26
10	Poor	Small	93	40	38	58
11	Poor	Medium	93	41	38	49
12	Fair	Medium	94	08	38	18
15	Poor	Large	94	12	38	18
16	Good	Large	94	07	38	14
19	Poor	Large	94	03	38	39
20	Poor	Medium	94	22	38	37
Average			94	01	38	35
Calculated			93	48	38	27

[a] Excluded from average.

Measurements of y{$\bar{1}01$}, meyerhofferite.

Crystal No.	Reflection.	Size of face.	ϕ		ρ	
			°	′	°	′
2	Poor.....	Minute.....	87	35	50	23
6	Poor.....	Minute.....	89	56	50	16
9	Poor.....	Medium....	87	30	50	22
12	Good.....	Medium....	87	21	50	19
15	Poor.....	Line face..	85	20	50	35
16	Poor.....	Minute.....	85	53	[a] 49	42
18	Poor.....	Minute.....	87	34	50	31
20	Poor.....	Line face..	84	48	50	44
Average [b].....			87	00	50	22
Calculated.....			87	10	50	21

[a] Excluded from average.
[b] The ϕ values vary so much that a general average was taken of all the angles.

Measurements of m{110}, meyerhofferite.

Crystal No.	Reflection.	Size of face.	ϕ		Crystal No.	Reflection.	Size of face.	ϕ	
			°	′				°	′
1	Fair.....	Small.....	54	34	14	Poor.....	Narrow....	54	04
2	Good....	Large.....	54	30	14	Fair.....	Narrow....	54	05
2	Poor.....	Line face..	[a] 54	09	15	Good....	Medium....	54	01
5	Poor.....	Small.....	54	30	16	Good....	Medium....	54	10
5	Good....	Small.....	54	28	17	Good....	Medium....	54	05
6	Fair.....	Medium....	[a] 55	12	18	Fair.....	Narrow....	54	18
6	Fair.....	Medium....	[a] 55	03	18	Fair.....	Medium....	[b] 54	28
9	Good....	Large.....	53	50	19	Fair.....	Medium....	54	19
10	Poor.....	Small....	[a] 55	10	20	Fair.....	Medium....	54	42
10	Poor.....	Medium....	[ab] 54	59					
11	Fair.....	Narrow....	54	01	Average of measurements.....			54	15
11	Poor.....	Narrow....	[b] 54	14	Average of good reflections.....			54	08
12	Fair.....	Medium....	54	06	Average of fair reflections.....			54	19
12	Poor.....	Line face..	[a] 54	38	Average of poor reflections.....			54	16
13	Fair.....	Medium....	[b] 54	22	Calculated.....			54	13
13	Good....	Medium....	53	54					

[a] Excluded from average. [b] Striated.

Measurements of M{$1\bar{1}0$}, meyerhofferite.

Crystal No.	Reflection.	Size of face.	ϕ		Crystal No.	Reflection.	Size of face.	ϕ	
			°	′				°	′
1	Good....	Small.....	129	49	16	Fair.....	Medium....	129	53
2	Good....	Small [a]....	129	55	18	Fair.....	Medium....	129	54
6	Fair.....	Medium....	129	48	18	Poor.....	Line face..	[c] 129	20
9	Good....	Medium [a]..	129	33	19	Fair.....	Large [b].....	129	51
9	Poor.....	Medium [b]..	[c] 129	11	20	Poor.....	Medium....	129	49
10	Good....	Medium [a]..	129	57	21	Poor.....	Narrow....	[c] 130	10
11	Fair.....	Narrow....	129	33					
12	Fair.....	Medium [b]..	[c] 129	12	Average of 13 measurements...			129	49
12	Fair.....	Narrow....	129	45	Average of good reflections....			129	49
13	Poor.....	Narrow....	130	57	Average of fair reflections.....			129	47
15	Fair.....	Narrow....	129	46	Calculated.....			129	48

[a] Cleavage (?) face. [b] Striated face. [c] Excluded from average.

FORMS AND ANGLES.

A total of 27 forms was determined on the measured crystals of meyerhofferite. These may be grouped as follows:

Pinacoids: *a*{100}, *b*{010}, *c*{001}.
Positive prisms: *k*{370}, *l*{120}, *A*{350}, *j*{450}, *m*{110}, *q*{210}, *n*{520}, *s*{310}, *B*{510}, *r*{810}.
Negative prisms: *v*{3$\bar{5}$0}, *M*{1$\bar{1}$0}, *w*{4$\bar{3}$0}, *h*{3$\bar{1}$0}.
Positive domes: *t*{101}, *d*{12.0.11}, *e* {706}, *f*{605}, *g*{504}, *i*{705}, *x*{302}, *z*{12.0.1}.
Negative dome: *y*{$\bar{1}$01}.
Pyramid: *p*{111}.

The average of the measured angles is shown in the table below.

Measured and calculated angles of meyerhofferite.

No.	Letter.	Number of crystals.	Number of measurements.	Symbol.	Measured.				Calculated.			
					ϕ		ρ		ϕ		ρ	
					°	′	°	′	°	′	°	′
1	*c*	6	6	001	−89	47	11	48	−88	59	11	41
2	*b*	20	33	010	0	00	90	00	0	00	90	00
3	*a*	20	37	100	93	12	90	00	93	13	90	00
4	*k*	2	2	370	29	33	90	00	29	39	90	00
5	*l*	1	1	120	33	51	90	00	33	44	90	00
6	*A*	2	3	350	39	01	90	00	38	55	90	00
7	*j*	1	1	450	46	58	90	00	47	32	90	00
8	*m*	16	29	110	54	15	90	00	54	13	90	00
9	*q*	1	1	210	71	56	90	00	71	37	90	00
10	*n*	3	4	520	75	31	90	00	75	43	90	00
11	*s*	2	2	310	78	50	90	00	78	32	90	00
12	*B*	1	1	510	84	13	90	00	84	20	90	00
13	*r*	2	2	810	87	54	90	00	87	39	90	00
14	*v*	3	4	3$\bar{5}$0	143	20	90	00	143	30	90	00
15	*M*	16	23	1$\bar{1}$0	129	49	90	00	129	48	90	00
16	*w*	3	3	4$\bar{3}$0	122	41	90	00	122	26	90	00
17	*h*	5	6	3$\bar{1}$0	107	55	90	00	107	30	90	00
18	*t*	13	13	101	94	01	38	35	93	48	38	27
19	*d*	1	1	12. 0. 11	94	16	40	53	93	44	41	30
20	*e*	1	1	706	94	03	43	45	93	42	43	50
21	*f*	2	2	605	93	40	44	35	93	40	44	50
22	*g*	2	2	504	93	52	45	56	93	39	46	14
23	*i*	1	1	705	93	45	49	50	93	36	50	03
24	*x*	1	1	302	93	45	52	12	93	34	52	18
25	*z*	1	1	12. 0. 1	93	03	84	21	93	15	85	09
26	*y*	10	10	$\bar{1}$01	−87	00	50	22	−87	10	50	21
27	*p*	15	15	111	47	34	46	54	47	35	47	01

c{001}. The basal pinacoid is represented in most of its occurrences as a broad line face between the positive and negative unit domes. On one crystal, No. 6, it is a large face lying between the line faces of the two domes. Its average size relative to the other terminal forms is shown in the orthographic projection of crystal 12

shown in figure 49 (p. 53). The angles on which the form is based are shown below:

Measurements of c{001}, meyerhofferite.

Crystal No.	Reflection.	Size of face.	Measured.		Calculated.	
			ϕ	ρ	ϕ	ρ
			° ′	° ′	° ′	° ′
6.....	Fair ..	Large.....	−89 56	11 51	−88 59	11 41
7.....	Poor...	Small.....	−88 37	11 50	−88 59	11 41
8.....	Poor...	Line face..	−86 00	12 00	−88 59	11 41
9.....	Poor...	Small.....	−89 36	12 00	−88 59	11 41
12.....	Poor...	Line face..	−85 52	11 37	−88 59	11 41
20.....	Poor...	Line face..	−89 41	11 45	−88 59	11 41

b{010}. It is not always possible to determine whether a certain face of *b* is natural or due to the perfect cleavage which is parallel to this form. The natural faces are mostly line faces, very narrow as compared with the other faces in the prism zone. Rarely they become broader, though most of the occurrences of broad *b* faces are clearly due to cleavage.

a{100}. The macropinacoid is the dominant form of the mineral and is developed on many crystals as a broad face vertically striated. The relatively large size of the *a* face causes the crystal to become tabular parallel to it, as shown in figures 42, 46, 49, 50, and 51. On a few crystals it is equaled in size by some other form in the prism zone. On 8 of the 10 crystal drawings of meyerhofferite chosen to show the various habits and combinations *a*{100} is the largest form. The measurements of the faces of *a*{100} have already been given under the calculation of the elements.

m{110} and *M*{1$\bar{1}$0}. The unit prisms are of medium size, varying from line faces to faces nearly as large as those of *a*{100}, but generally are about half as large or somewhat less. The faces are striated vertically, although not so strongly as those of *a*{100}. The average size of *m*{110} is somewhat larger than that of *M*{1$\bar{1}$0}.

The other prism forms, with the exception of *A*{350}, *j*{450}, *n*{520} and *v*{350}, are all line faces. Some of these prisms were observed but once and their measured angles are shown in the table just given. The values for those prisms which were measured more than once are given in the following table:

Measurements of rare prisms of meyerhofferite.

Form.	Crystal No.	Reflection.	Size of face.	φ Measured		φ Calculated	
				°	′	°	′
A (350)..	4	Good....	Small.....	39	01	38	55
	4	Poor.....	Small.....	38	11	38	55
	9	Poor.....	Line face.....	39	50	38	55
n (520)..	3	Poor.....	Broad, striated.....	76	00	75	43
	5	Good....	Small.....	75	20	75	43
	5	Good....	Small.....	75	16	75	43
	18	Poor.....	Line face.....	75	54	75	43
s (310)..	12	Poor.....	Line face.....	78	41	78	32
	21	Poor.....	Line face.....	79	00	78	32
r (810)...	18	Poor.....	Line face.....	87	57	87	39
	20	Poor.....	Line face.....	87	50	87	39
v (3$\bar{5}$0)..	4	Good....	Small.....	143	20	143	30
	14	Poor.....	Narrow.....	143	30	143	30
	14	Fair	Narrow.....	143	29	143	30
	21	Poor.....	Line face.....	143	01	143	30
w (4$\bar{3}$0)..	1	Poor.....	Line face.....	122	35	122	26
	7	Poor.....	Line face.....	122	45	122	26
	19	Poor.....	Line face.....	122	43	122	26
h (3$\bar{1}$0)..	12	Poor.....	Line face.....	107	13	107	30
	12	Poor.....	Line face.....	108	16	107	30
	13	Poor.....	Line face.....	107	54	107	30
	14	Poor.....	Line face.....	107	21	107	30
	17	Poor.....	Line face.....	108	43	107	30
	18	Poor.....	Line face.....	108	05	107	30

t{101}. The positive unit macrodome is one of the three dominant terminal forms, the other two being *y*{$\bar{1}$01} and *p*{111}. The faces of this form are generally large, though on a few crystals it occurs as a narrow face. The form is shown on a number of the crystal drawings (figs. 46, 47, 48, 49, 50, and 51). It has not been observed as the only terminal form, although crystal 13 is terminated by a single form, namely *f*{605} which is very near *t*{101}.

y{$\bar{1}$01}. The negative unit dome occurs nearly as frequently as *t*{101} but is smaller in size and in several crystals is present as a line face. The form is the only negative dome observed. It is shown in figures 48 and 49.

The remaining domes, seven in number, form a remarkable series in that five of them are very close to *t*{101} and, if each one occurred separately on a distinct crystal, would be considered as all belonging to a single form vicinal to the unit dome. The faces of these domes, however, are distinct and yield separate reflections and occur in such

a way as not to allow their being grouped together as one form. The occurrence of the forms in the zone $a(100)$, $c(001)$, $d(\bar{1}00)$ is shown below for the crystals containing domes other than the unit domes.

Occurrence of forms in the zone a{100}: a′{$\bar{1}$00}, meyerhofferite.

Crystal 11.	Crystal 13.	Crystal 19.	Crystal 20.
$\bar{1}00$	$\bar{1}00$	$\bar{1}00$	$\bar{1}00$
.....	.....	.....	$\bar{1}01$
.....	.....	.....	001
101	.....	101	101
.....	.....	.....	12. 0. 11
.....	.....	.....	706
.....	[a] 605	.....	605
504	.....	.....	504
.....	.....	705	.....
.....	.....	302	.....
.....	.....	12. 0. 1	.....
100	100	100	100

[a] The only terminal form on this crystal.

The occurrence of the two series of domes shown on crystals 19 and 20 is very unusual for these crystals.

The two measurements for $f\{605\}$ and $g\{504\}$ are shown below.

Measurements of f{605} and g{504}, meyerhofferite.

Form.	Crystal No.	Reflection.	Size of face.	Measured.		Calculated.	
				ϕ	ρ	ϕ	ρ
				° ′	° ′	° ′	° ′
$f\{605\}$	13	Poor...	Large.....	93 16	44 26	93 40	44 50
	20	Poor...	Line face...	94 03	44 43	93 40	44 50
$g\{504\}$	11	Poor...	Line face..	93 41	45 37	93 39	46 14
	20	Poor...	Line face..	94 03	46 14	93 39	46 14

The remaining domes are all line faces giving poor reflections and the angles measured are shown in the table on page 45.

Crystal 20, with its wealth of domes, is shown in figure 51 (p. 53).

The common forms of meyerhofferite, or those observed on at least ten crystals, are $b\{010\}$, $a\{100\}$, $m\{110\}$, $M\{1\bar{1}0\}$, $t\{101\}$, $y\{\bar{1}01\}$, and $p\{111\}$. The less common forms, observed on three to nine crystals, are $c\{001\}$, $n\{520\}$, $v\{3\bar{5}0\}$, $w\{4\bar{3}0\}$, $h\{3\bar{1}0\}$. The remaining forms, 15 in number, are all rare; 9 of them were observed only once.

COMBINATIONS.

The combinations observed on the 21 measured crystals of meyerhofferite are shown in the following table:

Combinations of forms on meyerhofferite crystals.

Letter.	Symbol.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
c	001						*c*	*c*	*c*	*c*			*c*								*c*	
b	010	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*		*b*	*b*	*b*	*b*	*b*	*b*	*b*
a	100	*a*	*a*	*a*	*a*		*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
k	370	*k*																*k*				
l	120												*l*									
A	350				*A*					*A*												
j	450																				*j*	
m	110	*m*	*m*			*m*	*m*			*m*	*m*	*m*	*m*	*m*		*m*	*m*	*m*	*m*	*m*	*m*	*m*
q	210																		*q*			
n	520			*n*		*n*													*n*			
s	310												*s*									*s*
B	510																		*B*			
r	810																		*r*		*r*	
v	350				*v*										*v*							*v*
M	$1\bar{1}0$	*M*	*M*				*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*		*M*	*M*		*M*	*M*	*M*	*M*
w	$4\bar{3}0$	*w*						*w*												*w*		
h	$3\bar{1}0$												*h*	*h*	*h*			*h*	*h*			
t	101			*t*			*t*	*t*	*t*	*t*	*t*	*t*	*t*		*t*	*t*	*t*			*t*	*t*	
d	12. 0. 11																				*d*	
e	706																				*e*	
f	605													*f*							*f*	
g	504											*g*									*g*	
i	705																			*i*		
x	302																			*x*		
z	12. 0. 1																			*z*		
y	$\bar{1}01$		*y*				*y*	*y*	*y*	*y*			*y*			*y*	*y*		*y*		*y*	
p	111	*p*	*p*	*p*				*p*	*p*	*p*	*p*	*p*	*p*		*p*	*p*			*p*	*p*	*p*	*p*

ZONAL RELATIONS.

The zonal relations are very well developed on the crystals of meyerhofferite, all the forms lying in three zones, and 96 per cent of the forms lying in two zones, namely, the prism zone with 16 forms and the macrodome zone with 11 forms, as shown in figure 41. The

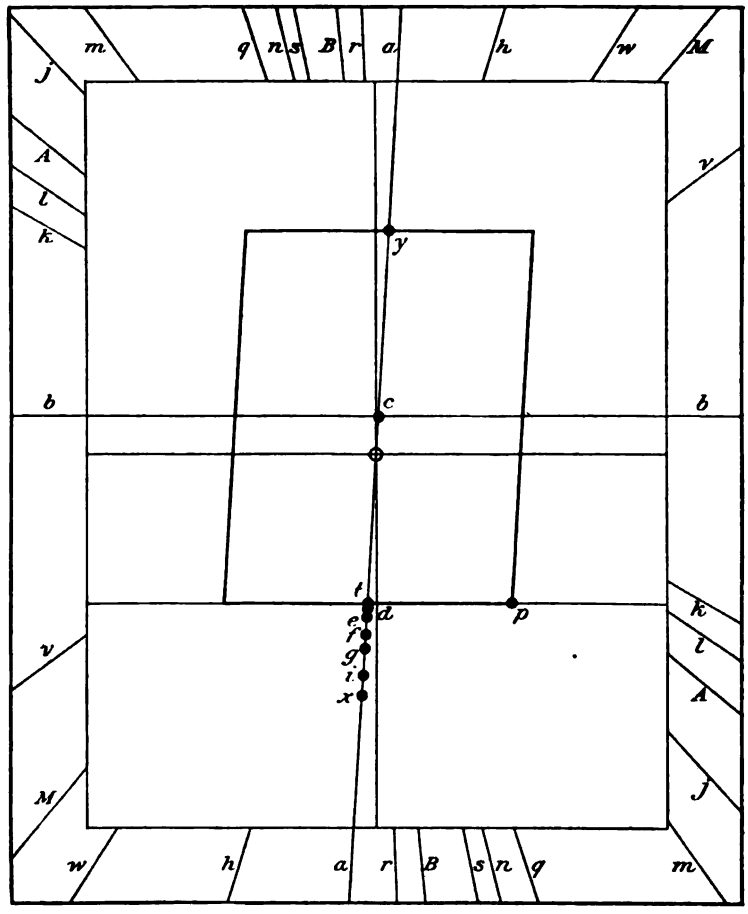

FIGURE 41.—Gnomonic projection of meyerhofferite forms. The form $z\{12.\ 0.\ 1\}$, not shown, falls outside of the projection.

unit pyramid $p\{111\}$ lies in such zones as $c\{001\}$, $p\{111\}$, $m\{110\}$, and $t\{101\}$, $p\{111\}$, $b\{010\}$.

The prism zone is characteristically striated vertically, and the macropinacoid shows the striations most prominently.

HABITS.

The crystals of meyerhofferite are all prismatic, but a distinction may be made between the tabular prismatic crystals and those with ~ual horizontal thickness. The tabular habit is caused by the

large development of the macropinacoid $a\{100\}$, as shown in figure 42. The prisms $m\{110\}$ and $M\{1\bar{1}0\}$ are both very narrow on such tabular crystals. As the crystals become thicker the $a\{100\}$ faces decrease in size, with a consequent enlargement of the prisms, as shown in figure 43. When one or both of the prisms equals the

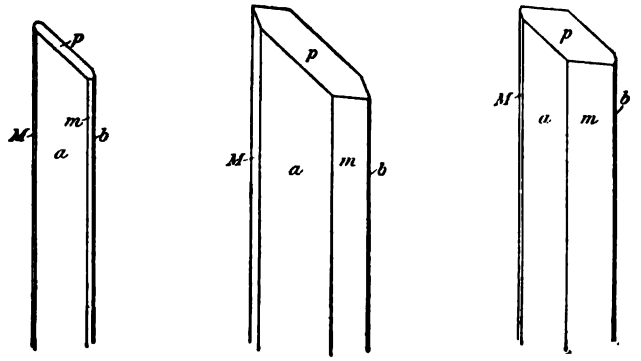

FIGURE 42. FIGURE 43. FIGURE 44.

FIGURE 42.—Tabular prismatic crystal (No. 1) of meyerhofferite. Forms: $b\{010\}$, $m\{110\}$, $a\{100\}$, $M\{1\bar{1}0\}$, $p\{111\}$.

FIGURE 43.—Crystal 21, meyerhofferite. Intermediate in habit.

FIGURE 44.—Crystal 2, meyerhofferite. Nearly equally thick in horizontal directions.

macropinacoid in size, the crystal becomes of nearly the same horizontal thickness in every direction, as shown in figure 44 and also in figure 50 (p. 53). A crystal (No. 17) which has a nearly square cross section is shown in orthographic projection in figure 45. Only the prism zone is developed on this crystal. The faces of $b\{010\}$ do not seem to be cleavage faces, and in the large development of the faces of the clinopinacoid b the crystal is unusual.

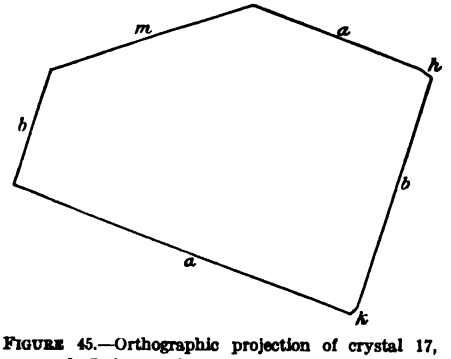

FIGURE 45.—Orthographic projection of crystal 17, meyerhofferite. Only the prism zone is shown on this crystal. Forms: $b\{010\}$, $a\{100\}$, $m\{110\}$, $k\{370\}$, $h\{3\bar{1}0\}$.

The terminations of meyerhofferite crystals consist either of a single large face or of three large faces, with perhaps one or two minute accompanying line faces. A termination showing a richer combination is very rare.

The single termination consists of the unit pyramid $p\{111\}$ (crystal 1, fig. 42) and in one crystal of the dome $f\{605\}$. In a crystal whose termination is composed of two forms they may be either $t\,p$ (as in crystal 10, fig. 46, and crystal 3, fig. 47), $t\,y$ (as in crystal 16, fig. 50, in which the rear dome $y\{101\}$ is not shown), or $p\,y$ (as in crystal 2, fig. 44, in which the rear dome $y\{101\}$ is likewise not shown). The

presence of three large terminal faces (t y p) is shown in clinographic projection in figure 48 (crystal 8) and in orthographic projection in figure 49 (crystal 12). In crystals in which the three forms all show large faces the basal pinacoid $c\{001\}$ is usually present as a line face. None of the terminal faces can be said to exert a decided influence on the habit of the crystals. The forms t y and p exert an equal influence, the faces of the other terminal faces being small.

MEASURED CRYSTALS.

The tabular to thicker crystals have already been illustrated in figures 42 to 45, which show the chief forms on crystals 1, 21, 2, and 17.

Crystal 2, figure 44, shows only $y\{\bar{1}01\}$ in addition to the forms figured, whereas on the other crystals a number of other forms, especially line-face prisms, are present.

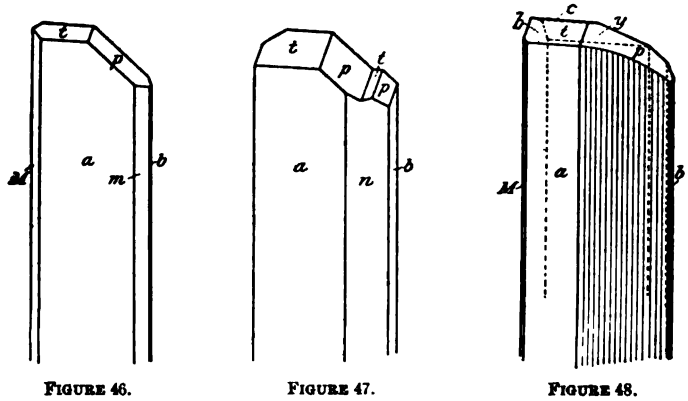

FIGURE 46. FIGURE 47. FIGURE 48.

FIGURE 46.—Crystal 10, meyerhofferite. Forms: $b\{010\}$, $m\{110\}$, $a\{100\}$ $M\{1\bar{1}0\}$, $t\{101\}$, $p\{111\}$.
FIGURE 47.—Crystal 3, meyerhofferite. Forms: $b\{010\}$ cleavage, $n\{520\}$, $a\{100\}$, $t\{101\}$, $p\{111\}$.
FIGURE 48.—Crystal 8, meyerhofferite. Forms: $b\{010\}$ $a\{100\}$, $M\{1\bar{1}0\}$, $t\{101\}$, $y\{\bar{1}01\}$, $c\{001\}$, $p\{111\}$. The large unlettered prism is so rounded and striated as to be undeterminable.

Crystal 10, figure 46, has only the two terminal forms shown in the drawing, which in fact represents the complete combination of the crystal as determined.

Crystal 3, figure 47, similarly has only the two terminal forms t and p, which have developed in a steplike form. The clinopinacoid faces, which may possibly be due to cleavage, are unusually large. The large development of the single face of $n\{520\}$ is noteworthy. The face is strongly striated.

Crystal 8, figure 48, shows a similar large striated face between $a\{100\}$ and $b\{010\}$, which, however, is so rounded and striated that it could not be determined. It may be a face of $n\{520\}$, like that on crystal 3 (fig. 47), or it may be the unit prism or a combination of several prisms. One side of the crystal is determined by a large cleavage face of $b\{010\}$. The termination shows $t\{101\}$, $y\{\bar{1}01\}$,

and $p\{111\}$, all large, with the basal pinacoid, $c\{001\}$, between the domes as a line face.

A terminal combination, similar to that on crystal 8, shown in figure 48, is present on crystal 12, and is shown in figure 49 in orthographic projection, in order to show better the relative size of the four forms.

In addition to the forms shown in figure 49, line faces of the rare prisms $l\{120\}$, $s\{310\}$, and $h\{3\bar{1}0\}$ are present on the crystal.

Crystal 16, figure 50, shows a large face of $t\{101\}$ and a minute one (not shown in the figure) of $y\{101\}$ as the only terminal forms. In general appearance, crystal 13 (not shown) is very similar to crystal 16 (fig. 50), except that the large terminal face is not $t\{101\}$ but the rare dome $f\{605\}$.

A series of domes are well developed on crystals 20 and 21, and crystal 20 is shown in figure 51. The forms $c\{001\}$ and $y\{\bar{1}01\}$ are present as line faces, but

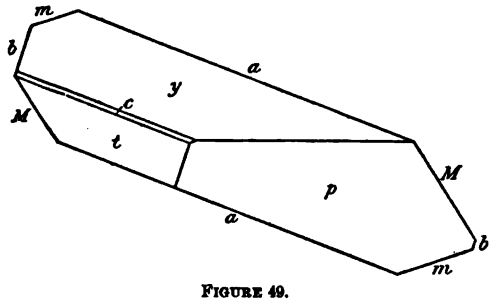

FIGURE 49.

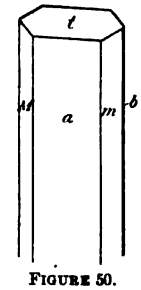

FIGURE 50.

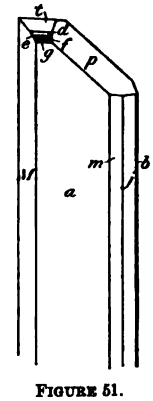

FIGURE 51.

FIGURE 49.—Orthographic projection of crystal 12, meyerhofferite. Forms: $b\{010\}$, $m\{110\}$, $a\{100\}$, $M\{1\bar{1}0\}$ $t\{101\}$, $c\{001\}$, $y\{\bar{1}01\}$, $p\{111\}$.

FIGURE 50.—Crystal 16, meyerhofferite. Forms: $b\{010\}$, $m\{110\}$, $a\{100\}$, $M\{1\bar{1}0\}$, $t\{101\}$.

FIGURE 51.—Crystal 20, meyerhofferite. The series of domes is notable. Forms: $b\{010\}$, $j\{450\}$, $m\{110\}$, $a\{100\}$, $M\{1\bar{1}0\}$, $g\{504\}$, $f\{605\}$, $e\{706\}$, $d\{12.0.11\}$, $t\{101\}$, $p\{111\}$.

are not shown in the drawing. The presence of a single large face of $j\{(450\}$ is notable, and a line face of $r\{810\}$ (not shown in the figure) was also determined.

Crystal 6, not shown, is unusual in having a large face of the basal pinacoid $c\{001\}$, while both domes t and y are minute line faces.

PHYSICAL PROPERTIES.

The cleavage of meyerhofferite is perfect parallel to the clinopinacoid, $b\{010\}$. Indications of other less perfect cleavages in the prism zone were encountered during the measurement of the crystals. Such indications were noted a number of times for $a\{100\}$ and $M\{1\bar{1}0\}$. The perfect clinopinacoidal cleavage causes the crystals to break readily in thin prisms. The hardness of the mineral is about 2.

The density of meyerhofferite, determined on colorless, transparent crystals by means of heavy solution, is 2.120. The same value was obtained on the artificial mineral by Van't Hoff and Meyerhoffer.[1]

[1] Van't Hoff, J. H., Untersuchungen über die Bildung der ozeanischen Salzablagerungen, LI. Künstliche Darstellung von Colemanit: Preuss. Akad. Wiss. Sitzber., 1906, p. 689.

The white opaque prisms of meyerhofferite have apparently a slightly lower density, but the lower value is more apparent than real and is probably due to a small amount of air inclosed in the partly cleaved crystals.

OPTICAL PROPERTIES.

Meyerhofferite crystals that have not been affected by outside influences are colorless; others are white. The luster is vitreous and on the opaque white masses somewhat silky. The colorless crystals are transparent; the white ones translucent to opaque.

The extinction on $b\{010\}$ is $c \wedge X' = 33°$; on $a\{100\}$ it is $c \wedge Z' = 25°$. The plane of the optic axis is across the elongation (c) and the obtuse bisectrix (Z) makes a moderate angle with the normal to the face (100). The axial angle $2V$ is nearly 90°, but the bars are perceptibly curved. The mineral is optically negative.

The refractive indices, as determined by the immersion method by Mr. Esper S. Larsen, for sodium light, are as follows: $\alpha = 1.500$, $\beta = 1.535$, $\gamma = 1.560$. The birefringence ($\gamma - \alpha$) is high, 0.060.

CHEMICAL PROPERTIES.

PYROGNOSTICS.

Meyerhofferite when heated in a blowpipe flame fuses readily without decrepitation but with intumescence to an opaque white enamel, imparting a greenish color to the flame. Heated in a closed tube, it fuses, giving off abundant water. The mineral is readily soluble in acids.

QUANTITATIVE COMPOSITION.

Two analyses were made of meyerhofferite, one on 0.0607 gram of the colorless transparent crystals, and one on gram and half-gram portions of the abundant opaque white variety. The boric acid had to be determined by difference in the colorless crystals. Both analyses yield the same result, as shown above.

Analyses and ratios of meyerhofferite.

	Opaque, white, fibrous mass.					Colorless, transparent crystals.	Calculated.
	1	2	3	Average.	Ratios.		
CaO	25.23	25.66	.....	25.45	2.05 or 2	25.6	25.02
B_2O_3	46.40	.....	.....	46.40	2.99 or 3	[45.6]	46.85
H_2O (below 110°)	1.01	.....	.....	1.01	.....	.3	.00
H_2O (above 110°)	[a] 27.75	[a] 28.00	[b] 27.49	27.75	6.96 or 7	28.5	28.13
	.....	.....	.....	100.61	.....	100.00	100.00

[a] Loss on ignition. [b] Loss on ignition with ignited CaO.

The ratios yield the formula $2CaO.3B_2O_3.7H_2O$, and the analysis of the colorless transparent crystals agrees well with that of the opaque, white, fibrous mass. Both analyses are also in close agreement with the calculated composition given in the last column.

The new minerals meyerhofferite and inyoite belong to the colemanite series of compounds. Of the compounds of $2CaO.3B_2O_3$ with water the following are known:

$2CaO.3B_2O_3.5H_2O$ (artificially prepared), colemanite.
$2CaO.3B_2O_3.7H_2O$ (artificially prepared), meyerhofferite.
$2CaO.3B_2O_3.9H_2O$ (artificially prepared).
$2CaO.3B_2O_3.11H_2O$.
$2CaO.3B_2O_3.13H_2O$, inyoite.

SYNTHESIS.

Meyerhofferite was artificially prepared by Meyerhoffer and Van't Hoff [1] by the following method. The hexahydrate of calcium monoborate, $CaO.B_2O_3.6H_2O$, was treated with boric acid solution at 100°, when the compound $2CaO.3B_2O_3.9H_2O$ was formed in well-crystallized augite-like forms. By heating this enneahydrate with a 3 per cent boric acid solution at 100° the compound $2CaO.3B_2O_3.7H_2O$ was formed in well-crystallized long rectangles.

DIAGNOSTIC PROPERTIES.

The prismatic, partly tabular crystals, perfect cleavage, and inclined (triclinic) extinctions serve, with the chemical tests, to distinguish meyerhofferite from all other natural borates.

[1] Meyerhoffer, Wilhelm, and Van't Hoff, J. H., Krystallisirte Calcium-borate: Annalen der Chemie, vol. 351, p. 100, 1907

LUCINITE, A NEW MINERAL: A DIMORPHOUS FORM OF VARISCITE.

ORIGIN OF INVESTIGATION.

A short time after the description of crystallized variscite from Utah[1] had been finished, Messrs. Edison & Bird, of Lucin, Utah, kindly furnished, in response to a request from the writer, several specimens which showed minute octahedral crystals associated with the tabular crystals of variscite. Preliminary measurements showed a close resemblance, in angular values, to variscite, and in a short note[2] these octahedral crystals were referred to as variscite. Subsequent more extended measurements showed, however, that although the angular values were close, they could not be referred to those of variscite. The mature consideration of the problem has led to the conclusion that the octahedral crystals belong to a second modification of the same chemical compound as variscite, and the new mineral is named lucinite. The specimens that show crystals of lucinite are scarce, but it is not improbable that a search at the locality for more material would show that the new mineral occurs in some abundance. In the compact granular phase lucinite is not distinguishable from variscite. In fact, it is impossible from our present knowledge of these two minerals to say whether the compact material used in jewelry[3] is variscite or lucinite.

Mr. G. W. Fiss, of Philadelphia, kindly sent to the writer a quantity of variscite from Lucin, Utah, in which were found several specimens of lucinite that were a welcome addition to the meager quantity at hand.

NOMENCLATURE AND LOCALITY.

The name lucinite is derived from the locality, the specimens having been found in the northern part of Utahlite Hill, 5 miles northeast of Lucin, Boxelder County, Utah.

PARAGENESIS.

Lucinite occurs in compact massive pieces that in thin section are seen to be composed of small equidimensional areas which, while optically units, only here and there show distinct crystal outline.

[1] Schaller, W. T., Crystallized variscite from Utah: U. S. Geol. Survey Bull. 509, p. 48, 1912.

[2] Schaller, W. T., The crystallography of variscite: Washington Acad. Sci. Jour., vol. 2, p. 143, 1912.

[3] Sterrett, D. B., Gems and precious stones: U. S. Geol. Survey Mineral Resources, 1910, pt. 2, pp. 894-896, 1912.

Numerous cavities are present in this massive phase and these cavities are lined with minute crystals of lucinite and variscite. Cavities can be seen containing only lucinite, others have only variscite, and in many others both minerals are present. The crystals of lucinite are found only in the cavities of the massive granular material, and on many specimens are directly associated with variscite crystals. In some of the material several crystals of lucinite were perched on a larger tabular crystal of variscite (fig. 52), and again a variscite crystal was seen to rest on a bed of smaller lucinite crystals (fig. 53). Such associations would indicate a more or less similar condition of formation of the two modifications. In many cavities lucinite forms the lining, and the variscite crystals are perched on this lining and seem, therefore, to be of later formation.

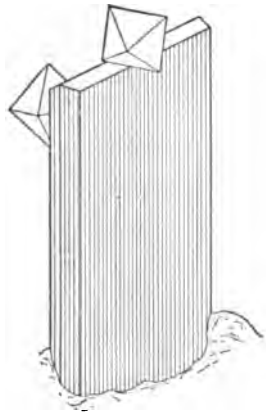

FIGURE 52.

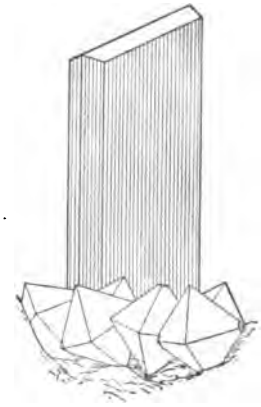

FIGURE 53.

FIGURE 52.—Octahedral crystals of lucinite perched on a larger tabular crystal of variscite.
FIGURE 53.—Tabular crystal of variscite resting on a bed of smaller crystals of lucinite.

The paragenesis of lucinite is the same as that of variscite, and the description given for variscite applies as well for the lucinite. The only identified associated minerals are variscite and massive quartz.

CRYSTALLOGRAPHY.

GENERAL CHARACTER OF CRYSTALS.

The crystals of lucinite are minute, the largest having a diameter of about 1 millimeter and most of them being much smaller. The six measured crystals were all less than 1 millimeter thick, ranging in size from about 0.2 to 0.5 millimeter. No twins were observed, and the crystals all had the same general octahedral habit.

CALCULATION OF ELEMENTS.

The minute crystals presented even and highly polished surfaces which gave distinct reflections that could be accurately measured. The basal pinacoid was present on most of the crystals and served to adjust them in polar position on the two-circle goniometer. The different faces of the same form were then utilized for further adjustment, and by a process of averaging the crystals were finally placed in correct polar position.

After the symmetry of the crystals had been determined, the two crystals yielding the best reflections, Nos. 1 and 2, were remeasured after being accurately adjusted in polar position. The measurements of the pyramids then gave values from which the axial ratio was calculated. The average of p_0 and q_0, obtained directly from the angles ϕ and ρ, are $p_0 = 1.1225$, $q_0 = 0.9788$. From these values, the axial ratio $a:b:c$ is calculated and found to be 0.8729:1:0.9788.

Values of p_0 and q_0, lucinite.

Crystal No.	Form.	p_0	q_0	Crystal No.	Form.	p_0	q_0
1.....	$i\{112\}$	1.1208	0.9760	1.....	$s\{121\}$	1.1269	0.9786
1.....	$i\{112\}$	1.1186	.9799	2.....	$i\{112\}$	1.1233	.9662
1.....	$i\{112\}$	1.1307	.9812	2.....	$i\{112\}$	1.1046	.9876
1.....	$i\{112\}$	1.1143	.9698	2.....	$i\{112\}$	1.1429	.9935
1.....	$p\{111\}$	1.1124	.9716	2.....	$i\{112\}$	1.1105	.9796
1.....	$p\{111\}$	1.1120	.9707	2.....	$p\{111\}$	1.1343	.9878
1.....	$p\{111\}$	1.1270	.9791	2.....	$p\{111\}$	1.1345	.9978
1.....	$p\{111\}$	1.1318	.9821	2.....	$p\{111\}$	1.1180	.9765
1.....	$s\{121\}$	1.1373	.9849	2.....	$p\{111\}$	1.1093	.9654
1.....	$s\{121\}$	1.1270	.9806				
1.....	$s\{121\}$	1.1147	.9679	Average..	.....	1.1225	.9788

The interfacial angles in the zone $c\ p$ were also measured on many of the crystals, and by expressing the measured angles in terms of the angle $c(001) : p(111)$,[1] the following values were obtained:

Interfacial measured angles in zone c p expressed as the angle c(001): p(111), lucinite.

Crystal 1.		Crystal 2.	Crystal 4.	Crystal 5.	Crystal 6.
° ′	° ′	° ′	° ′	° ′	° ′
56 07	56 06	56 03	56 10	56 23	56 08
56 05	56 08	56 06	56 09	56 06	56 02
56 09	56 04	56 11	56 10	56 03	56 07
56 11	56 00	.. ..	56 18	56 19	56 08
56 01	56 05	.. ..	56 15	56 13	55 57
55 55			56 12		
Av. 56 03.7		56 06.7	56 12.3	56 12.8	56 04.4

[1] Instance, the measured angle $p(111)$: $p(11\bar{1}) = 67° 47'$ would be changed to $90° - \frac{1}{2}(67° 47') = 56° 06\frac{1}{2}'$.

The average of 30 measurements on five crystals gives the value 56° 07.3′, whereas the angle (001): (111) calculated from the axial ratio $a:b:c=0.8729:1:0.9788$, as given above, is 56° 06.4′, thus serving as a check on the correctness of the axial ratios as given. Further evidence of the same fact is afforded by the close agreement between measured and calculated angles, as given on the following page.

FORMS AND ANGLES.

Eight forms were established for lucinite. These are distributed as follows:

Pinacoids: *c*{001}, *a*{100}.
Prism: *d*{120}.
Brachydome: *e*{012}.
Pyramids: *r*{113}, *i*{112}, *p*{111}, *s*{121}.

The averages of the measured angles as compared with the calculated values are shown in the following table:

Measured and calculated angles, lucinite.

[$a=0.8729$, $c=0.9788$, $p_0=1.1225$.]

No.	Letter.	Symbol.	Number of crystals.	Number of faces measured.	Measured.		Calculated.	
					ϕ	ρ	ϕ	ρ
					° ′	° ′	° ′	° ′
1	*c*	001	6	9	.....	0 00	.....	0 00
2	*a*	100	2	3	90 11	90 00	90 00	90 00
3	*d*	120	2	3	30 14	90 09	29 48	90 00
4	*e*	012	3	7	0 00	26 13	0 00	26 05
5	*r*	113	1	2	48 42	26 35	48 53	26 33
6	*i*	112	6	26	48 51	36 39	48 53	36 39
7	*p*	111	6	28	48 55	56 07	48 53	56 06
8	*s*	121	5	14	30 00	66 07	29 48	66 06

c{001}. The basal pinacoid is present on all the crystals measured but is not present on many of the lucinite crystals seen on the specimens. It is rectangular in shape and always small in comparison with the other forms.

a{100}. The macropinacoid was observed on only two crystals as minute faces. It is shown in the drawing of crystal 4 (fig. 61, p. 64).

d{120}. The prism *d* is also a rare form, being likewise observed on only two crystals. It forms a line face, as shown in figure 61, and the measurements of the three faces gave the following ϕ angles: 31° 00′, 29° 19′, 30° 23′; calculated, 29° 48′.

e{012}. The brachydome *e*{012} was determined on half the measured crystals as minute faces giving poor reflections. It is shown in figures 58 and 61. The measurements of the form are as follows:

Measurements of e{012}.

Crystal No.	Measured.		Calculated.	
	ϕ	ρ	ϕ	ρ
	° ′	° ′	° ′	° ′
2.....	0 00	26 28	0 00	26 05
2.....	0 10	26 30	0 00	26 05
4.....	0 07	26 07	0 00	26 05
4.....	0 00	26 10	0 00	26 05
6.....	0 04	26 05	0 00	26 05
6.....	0 04	26 02	0 00	26 05

r{113}. The pyramid *r* was determined on crystal 4, on which it occurred with two faces, in the zone *cp*. The ρ measurements of two faces gave 26° 35′, 26° 35′, the remaining two faces surrounding the rectangular base not being measurable because of their minute size. The form is shown in figure 61 (p. 64).

i{112}. This form is present on all the measured crystals as a narrow or broad line face surrounding the rectangular base. It is shown on many of the drawings illustrating the crystals of lucinite.

p{111}. The unit pyramid *p* is the dominant form of lucinite and determines the octahedral shape of the crystals. On many crystals it is evidently the only form, and, the axial ratio of the mineral being close to unity, crystals of lucinite showing only *p*{111} (fig. 55) closely resemble the octahedron of the isometric system (shown in fig. 87, p. 90, with which fig. 55 may be compared). Although the faces of *p* generally have a triangular shape, the large development of the faces of *s*{121} causes the *p* faces to become rhombic in shape, as shown in figures 59, 60, and 61.

s{121}. The pyramid *s* is the second largest form on the lucinite crystals and seems to be present on nearly all crystals which show any form in addition to *p*{111}. The faces of *s*{121} range in size from minute ones to some nearly as large as those of *p*{111}.

A number of other forms, of very simple indices—three of them, in fact, belonging to the "unit forms"—were observed and measured, but they were so minute that their measurements are several degrees from the calculated values. The forms are therefore not further described, but are given for comparison with possible future measurements. They are {010}, {110}, {101}, {102}.

COMBINATIONS.

The combinations observed on the six measured crystals are as follows:

Combinations on measured crystals of lucinite.

Form.	1	2	3 (fig. 57).	4 (fig. 61).	5	6 (fig. 58).
c{001}	*c*	*c*	*c*	*c*	*c*	*c*
a{100}	.....	.....	.....	*a*	.....	.....
d{120}	.....	.....	.....	*d*	.....	*d*
e{012}	.....	*e*	.....	*e*	.....	*e*
r{113}	.....	.....	.....	*r*	.....	.....
i{112}	*i*	*i*	*i*	*i*	*i*	*i*
p{111}	*p*	*p*	*p*	*p*	*p*	*p*
s{121}	*s*	*s*	.....	*s*	*s*	*s*

Besides the combinations given above, the following were commonly observed on crystals not measured but carefully examined with a hand lens: *p* (fig. 55), *p s* (fig. 56), *p c i* (fig. 57). The combination *p c i* is very common.

ZONAL RELATIONS.

The chief zone of lucinite is *c p*, with four forms in it, namely, *c*, *r*, *i*, and *p*. The zone (100) : (012) contains *a*, *i*, and *e*, and the zone (010): (101) the forms *s* and *p*. The prism zone has only *a* and *d*. The paucity of known forms on lucinite renders it difficult to say what are the chief zones. The relative positions of the zones can be seen in figure 54 (p. 62).

HABITS.

The crystals of lucinite show only the octahedral habit, somewhat modified by the large development of forms other than the unit pyramid. If *p*{111} is the only form present, then the crystals resemble an octahedron very much, as shown in figure 55. On some crystals small faces of *s*{121} are present (fig. 56), and on still others small faces of *c*{001} and *i*{112} appear (fig. 57). On many crystals both modifications occur together, as shown in figures 58, 59, and 60.

The large development of the faces of *s*{121}, although retaining the octahedral habit, causes the crystals to have a somewhat different appearance, as shown in figure 59. Many such crystals were seen on the specimens with a hand lens. Distorted crystals of this combination are very abundant, the faces of *s*{121} being large at one end and small at the opposite end. The faces of the basal pinacoid *c*{001} are likewise of different size on many crystals, one of which, as seen with a hand lens, is reproduced in figure 60 (p. 63).

Crystal 4, shown in figure 61, has all the observed forms of lucinite, and the combination, drawn in ideal symmetry as near like the actual crystal as possible, shows well the relative size and shape of the different forms of lucinite.

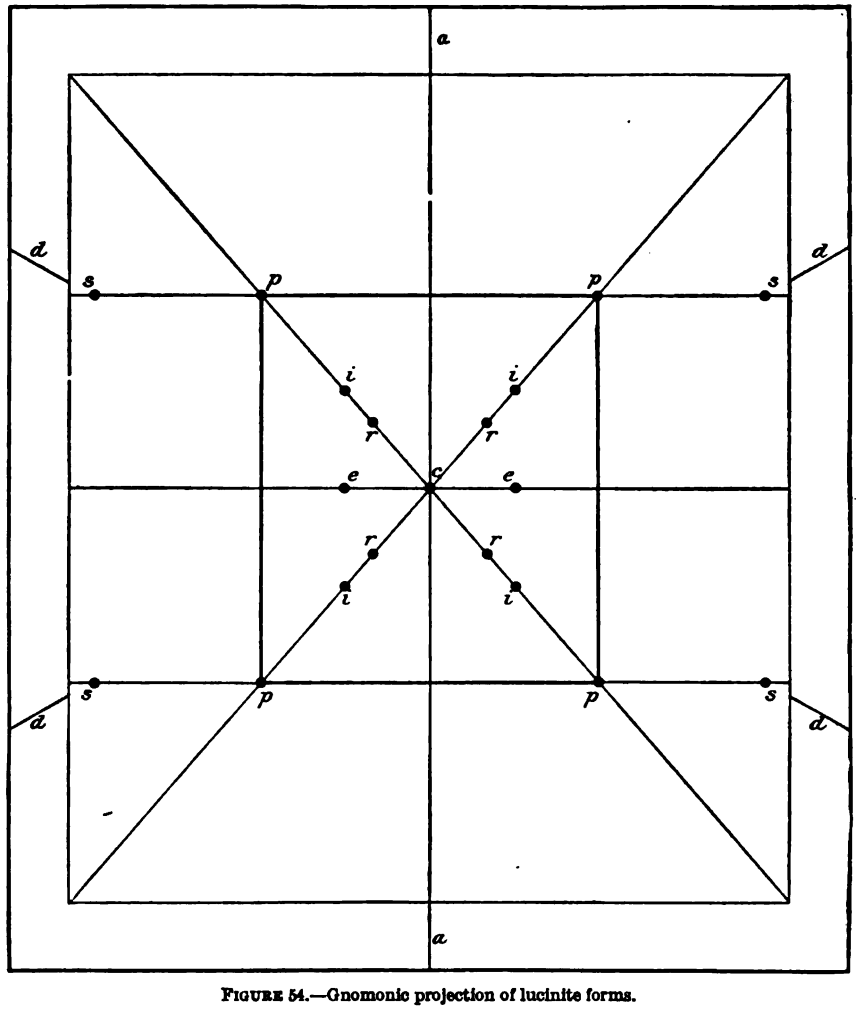

FIGURE 54.—Gnomonic projection of lucinite forms.

MEASURED CRYSTALS.

Crystal 1, not shown in any of the drawings, resembles the crystals shown in figures 59 and 60 in the large development of $s\{121\}$ and consequent rhombic shape of $p\{111\}$. The right half of figure 60 represents closely the habit and development of the forms on crystal 1.

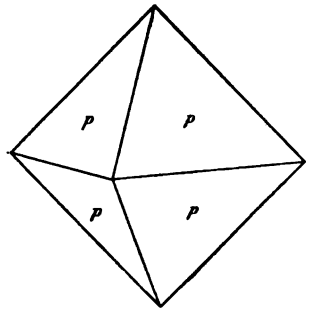

FIGURE 55.

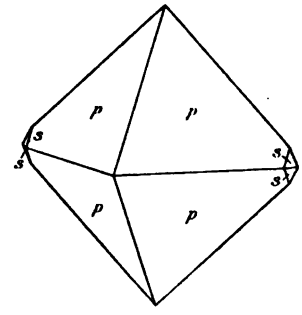

FIGURE 56.

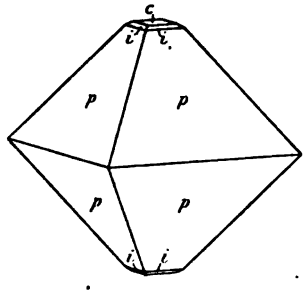

FIGURE 57.

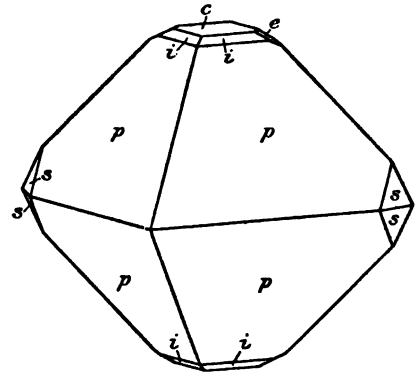

FIGURE 58.

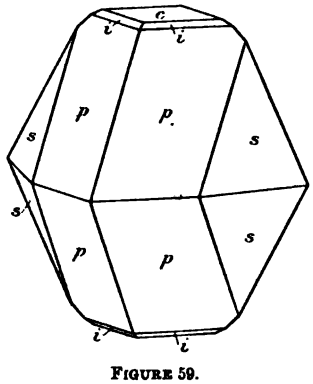

FIGURE 59.

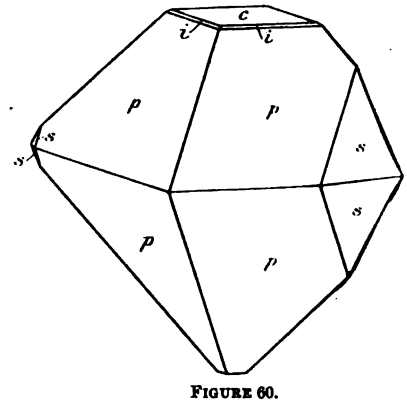

FIGURE 60.

FIGURE 55.—Octahedral crystal o. lucinite. Form: $p\{111\}$. Compare with figure 87 (p. 90).

FIGURE 56.—First modification of simple octahedral crystal of lucinite. Forms: $p\{111\}$ and $s\{121\}$.

FIGURE 57.—Second modification of simple octahedral lucinite on crystal 3. Forms: $p\{111\}$, $c\{001\}$, and $i\{112\}$.

FIGURE 58.—Both modifications occurring on lucinite crystal 6. Forms: $c\{001\}$, $e\{012\}$, $i\{112\}$, $p\{111\}$, $s\{121\}$.

FIGURE 59.—Lucinite crystal with large development of $s\{121\}$, with $c\{001\}$, $i\{112\}$, and $p\{111\}$.

FIGURE 60.—A distorted crystal of lucinite. Same combination as shown in figure 59.

Crystal 2 is like that shown in figure 58 except that the faces of $s\{121\}$ are perhaps still smaller. Both crystals 1 and 2 are well developed and the plane and brilliant faces give good reflections, which were measured for the calculation of the axial ratios of the mineral.

Crystal 3, figure 57, shows the simple combination *c i p*, which was also observed on many crystals that were not measured.

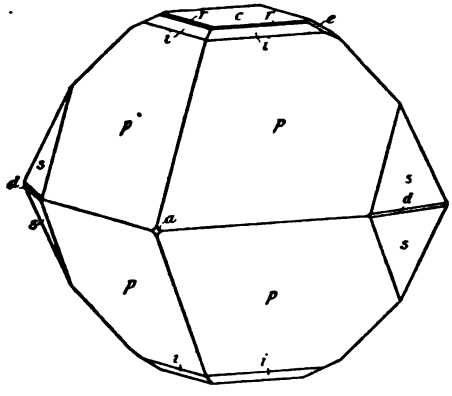

FIGURE 61.—Crystal 4, lucinite, showing all the eight forms of the mineral. Forms: $c\{001\}$, $a\{100\}$, $d\{120\}$, $e\{012\}$, $r\{113\}$, $i\{112\}$, $p\{111\}$, $s\{121\}$.

Crystal 4, figure 61, is remarkable for the many forms found on it; in fact, all the eight forms determined for lucinite were measured and identified on this crystal. Figure 61 represents a symmetrical development of the forms given, with their relative size as they occur on the crystal.

Crystal 6, figure 58, shows a line face of the prism $d\{120\}$, not shown in the drawing. The faces of $i\{112\}$ are somewhat broader than usual on this crystal. The three uncertain unit forms, given in the last line on page 60, were measured on this crystal.

RELATION TO OTHER MINERALS.

Lucinite falls naturally into the same mineral group as scorodite, as shown in the following table:

Scorodite group of minerals.

Name.	Formula.	*a* axis.	*c* axis.
Scorodite	$Fe_2O_3.As_2O_5 4.H_2O$	0.8658	0.9541
Strengite	$Fe_2O_3.P_2O_5.4H_2O$	.8652	.9827
Lucinite	$Al_2O_3.P_2O_5.4H_2O$	.8729	.9788
Phosphosiderite [a]	$Fe_2O_3.P_2O_5.3\frac{1}{2}H_2O$?	.8772	1.0660
Variscite	$Al_2O_3.P_2O_5.4H_2O$	.8944	1.0919
Vilateite [b]	?	.8479	.8886

[a] This orientation of phosphosiderite is obtained by interchanging the *a* and *c* axes in the position given by Dana and then doubling the new *a* axis.

[b] Vilateite is supposed to be similar to strengite in composition and is described as monoclinic, with $\beta = 89° 27'$, but the angular differences from orthorhombic symmetry are slight, and Lacroix (Mineralogie de la France, vol. 4, p. 477, 1910) states that optically the mineral behaves somewhat like an orthorhombic substance. Half of the *a* axis, as given by Lacroix, has been taken in the above table.

The close agreement in the axial ratios for strengite and lucinite on the one hand and those for variscite and phosphosiderite on the other, suggests that perhaps phosphosiderite is a dimorphous form of strengite and not identical with it, as the writer has previously suggested.[1] The formula would then, however, have to be like that of strengite and not $Fe_2O_3 \cdot P_2O_5 \cdot 3\frac{1}{2}H_2O$, as given in the literature. The varying data given for the angles of scorodite also strongly suggests the possibility that dimorphous minerals have been grouped together under the common name scorodite.

The angular relations of lucinite and variscite have been carefully studied, and it has not been possible so to orient them as to make both minerals referable to one axial ratio.

If the *b* and *c* axes of lucinite are interchanged, the *a* axis being retained as such, then the symbols of the forms change as follows, the axial ratio of lucinite, as given, being expressed as $a : b : c$, whereas the new orientation, due to the interchange of the *b* and *c* axes, is expressed as $a' : b' : c'$.

$a : b : c$	$a' : b' : c'$
100	100
010	001
001	010
110	101
101	110
011	011
111	111

The new axial ratio, $a' : b' : c'$, then becomes 0.8918 : 1 : 1.0217, which is closer to the ratio of variscite, namely, 0.8952 : 1 : 1.0957, than the ratio adopted for lucinite. The value of a' (lucinite) is nearly identical with a' (variscite), the ϕ angles of {110} being 48° 17′ and 48° 10′, respectively. It is to be noted, however, that the difference in the *c* axes is considerable.

c' (lucinite)=1.0217, $\rho\{011\}$=45° 37′
c (variscite)=1.0957, $\rho\{011\}$=47° 37′

The fact that the crystals of lucinite and of variscite are not identical in angular value can also be readily shown by the comparison of the angle between the unit pyramid $p\{111\}$ and the three pinacoids. There are only three pinacoids and of course only one unit pyramid in the orthorhombic system, so that the angles $a\ p$, $b\ p$, $c\ p$ would show at once any identical values between two orthorhombic minerals, no matter how they were oriented. As earlier given, the angle between one pinacoid and the unit pyramid was accurately measured on the lucinite crystals. In the orientation

[1] Schaller, W. T., Crystallized variscite from Utah: U. S. Geol. Survey Bull. 509, p. 61, 1912.

adopted for that mineral this is the angle $c\{001\} : p\{111\}$. This angle has a measured value of 56° 07′. The three pyramid-pinacoid angles of variscite are calculated to be $\{001\}:\{111\} = 58° 36'$, $\{010\}:\{111\} = 55° 20'$, $\{100\}:\{111\} = 50° 29'$, with none of which does the lucinite angle of 56° 07′ agree. The closest value is $\{010\}:\{111\} = 55° 20'$, which, however, differs 47′, or nearly 1°, from the lucinite angle.

The fact that the two modifications of a mineral occur together, as shown in figures 52 and 53 (p. 57), is by no means unusual. Compare, for instance, the occurrence of rutile, anatase, and brookite, described by Palache.[1]

PHYSICAL PROPERTIES.

Lucinite does not show any cleavage, and in that respect it resembles variscite. No indication of twinning was seen on the octahedral crystals of lucinite, whereas twinning on the associated variscite is by no means rare. (The twinning of variscite is described on p. 77.) The hardness of lucinite is about 5.

The density of lucinite was not accurately determined. The crystals are so minute that it is difficult to obtain a crystal absolutely free from any adhering gangue. The density was therefore determined on fragments of the granular material, which on analysis was found to contain 26.29 per cent of quartz. The results obtained were not altogether satisfactory. They are as follows, 25 small fragments about 2 millimeters in diameter being suspended in Thoulet solution:

Density.	Sank.	Floated.
2.576	3	22
2.573	9	16
2.558	19	6
2.548	24	1

The results indicate that the density of the specimens lies between 2.57 and 2.56, with perhaps 2.566 as an average value. Correcting these values for the 26.29 per cent admixed quartz (density 2.66) gives the density of lucinite as between 2.52 and 2.53. It is therefore nearly identical with that of variscite, which was determined on 1.3 grams of the tabular crystals by the pycnometer method to be 2.536, or in round numbers 2.54. The assumption that the granular material is lucinite and not variscite is based on the fact that all the drusy crystals coating cavities are lucinite. No tabular variscite crystals were seen on this material.

[1] Palache, Charles, Anatas, Brookit und Titanit von Somerville, Mass.: Rosenbusch Festschrift, p. 311, 1906.

OPTICAL PROPERTIES.

Lucinite is green and on being heated undergoes the same color change to deep lavender as the associated variscite. The luster is vitreous; the streak white or gray. The small fragments are transparent when bounded by parallel faces.

The optical orientation could not be determined.

The refractive indices are slightly higher than those of variscite. For instance, in crushed material all the indices are higher than 1.555, whereas for variscite $\alpha=1.546$, $\beta=1.556$, $\gamma=1.578$. The results of the examination have yielded minimum and maximum values for the indices and these may be tentatively given for the mineral as $\alpha=1.56$, $\gamma=1.59$. The birefringence, $\gamma-\alpha=0.03$, is high, about the same as that of variscite. On one section, an interference figure was observed with $2E$ large (at least about 100°). Its sign is negative, whereas variscite is positive.

The crystals are practically nonpleochroic, the color of the transmitted light being a pale green.

CHEMICAL PROPERTIES.

The pyrognostic properties of lucinite are the same as those of variscite.

A sample of the granular material whose cavities were lined with crystals of lucinite was analyzed and found to contain 26.29 per cent of silica, due to admixed quartz which was later identified in a thin section. The close similarity in crystal angles of lucinite and variscite made it imperative that the crystals of lucinite be analyzed. With great difficulty a sample was prepared which contained about 10 per cent of tabular variscite crystals, 10 per cent of granular material (lucinite or variscite?), and 80 per cent of octahedral crystals of lucinite. The entire sample analyzed weighed only 25 milligrams, but the results verified the fact that the composition of the octahedral lucinite crystals was the same as that of the tabular variscite crystals. The results obtained are shown below.

Analyses of lucinite.

	Granular material.	Same with quartz deducted.[a]	Octahedral crystals.[b]	Variscite tabular crystals.	Calculated for $Al_2O_3.P_2O_5.4H_2O$.
Al_2O_3	25.82	34.97	29	[c] 32.96	32.31
P_2O_5	31.56	42.75	44	44.73	44.93
H_2O	16.80	22.75	22	22.68	22.76
SiO_2	26.29	.....	1	.....	.....
	100.47	100.47	96	100.37	100.00

[a] Other impurities may have been present in the sample, but no allowance is made for them.
[b] Probably had about the following composition: Octahedral crystals, 80 per cent; tabular variscite crystals, 10 per cent; granular material, 10 per cent.
[c] The percentage of Al_2O_3 is 32.40. The figure given includes V_2O_3, 0.32; Cr_2O_3, 0.18; Fe_2O_3, 0.06.

The analyses agree well enough with the calculated values for the formula $Al_2O_3.P_2O_5.4H_2O$ to show that the chemical composition of lucinite and variscite are the same.

The amount of water given off by the granular mass of lucinite (which can not be told from granular variscite in the absence of crystals) at 100° is about the same as that found for variscite. At least, the available data are not sufficient to show whether or not the water is combined in a different way in lucinite than in variscite. All the water in lucinite is given off below 180°.

Lucinite contains a small amount of vanadium. No test was made for chromium, though doubtless it also is present. In fact, the chemical properties of lucinite and variscite have not shown any difference so far as they have been determined.

DIAGNOSTIC PROPERTIES.

The octahedral shape of the lucinite crystals serves to differentiate the mineral from the other crystallized aluminum phosphates.

THE CRYSTALLOGRAPHY OF VARISCITE.

PREVIOUS DESCRIPTION.

The crystallography of variscite was described by the writer[1] in 1912 as determined on material from Lucin, Utah. A collection of specimens was later sent to the Survey by Messrs. Edison & Bird, of Lucin, and on these specimens were noted numerous crystals of variscite which showed several different habits from that given in the original description. Knowledge of the crystallography of variscite has been considerably extended by the study of the new material, on which the following description is based.

The variscite crystals either form coarsely granular masses which are only loosely coherent or partly fill cavities in the granular material. Some of these cavities contain only variscite crystals; in others the variscite is intermingled with crystals of lucinite. (Compare description of occurrence of lucinite crystals, p. 57.)

GENERAL CHARACTER OF CRYSTALS.

Eighteen crystals were detached and measured on the two-circle goniometer. The crystals averaged about 1 millimeter in length and were much smaller in their other dimensions. They are both simple and twinned crystals. The general habit is tabular, with several modifications, as described beyond.

CALCULATION OF ELEMENTS.

The measured crystals of variscite yielded additional angular values which are close to those earlier obtained. The fundamental angles from which the axial ratio was calculated in the published description of the variscite crystals are shown below, with the present measurements given immediately beneath them.

Former measurement: (010):(110)=48° 10′.6, (010):(012)=61° 17′.
Present measurement: (010):(110)=48° 12′.6, (010):(012)=61° 25′.5.

A new value for variscite was therefore calculated by combining the former and the present measurements. The new axial ratio varies but slightly from the published ratio but is somewhat more accurate. From the 22 good measurements of $m\{110\}$ here given an average value of 48° 12′.6 is calculated for the ϕ angle. This is almost identical with the value earlier calculated as the average of 26 measurements, namely, 48° 10′.6. The average of these two values gives 48° 11′.5, from which the a axis is calculated as 0.8944. From the

[1] Schaller, W. T., Crystallized variscite from Utah: U. S. Geol. Survey Bull. 509, p. 57, 1912.

17 good measurements of $e\{012\}$ is obtained an average of 28° 34′.5, which is slightly different from the previous value of 28° 43′. An average value of 1.0919 is obtained for c, as follows:

Average of 17 measurements, ρ (012)=28° 34′.5, c=1.0893
Average of 12 measurements, ρ (012)=28° 43′, c=1.0957

Average of 29 measurements, c=1.0919

The new value for the axial ratio of variscite, as calculated, is therefore

$$a:b:c=0.8944:1:1.0919. \quad p_0=1.2208.$$

The former value was $a:b:c=0.8952:1:1.0957$.

The measured angles of $m\{110\}$ and $e\{012\}$, from which the axial ratio was calculated, are given in the following table. For comparison the measurements of those faces which gave poor reflections are also included, but they were excluded from the average value of the good reflections.

Measurements of m{110} and e{012} variscite.

Crystal No.	m{110}		e{012}	
	Good reflection.	Poor reflection.	Good reflection.	Poor reflection.
	° ′	° ′	° ′	° ′
1	48 28	48 06	28 37	.....
1	.....	47 27	28 26	.....
2	48 22	47 47	28 39	28 31
3	48 23	48 19	28 34	.....
3	.....	.....	28 36	.....
5	.....	.....	28 34	.....
6	48 06	.....	.....	.....
6	.....	.....	.....	.....
7	.....	.....	28 39	.....
8	48 08	.....	.....	28 49
9	.....	.....	28 29	.....
11	48 05	48 19	28 43	28 58
12	48 09	.....	.....	28 33
12	47 49	.....	.....	.....
12	48 14	.....	.....	.....
13	48 15	.....	28 31	.....
13	48 04	.....	28 36	.....
13	48 13	.....	.....	.....
13	48 27	.....	.....	.....
15	48 09	.....	28 35	.....
15	.....	.....	28 31	.....
16	48 32	.....	28 32	.....
16	48 04	.....	28 36	.....
16	48 16	.....	.....	.....
16	47 51	.....	.....	.....
17	47 51	47 36	28 33	28 31
18	48 26	.....	28 35	.....
18	48 21	.....	.....	.....
18	48 24	.....	.....	.....
Average	48 12.6	47 56	28 34.5	28 40

FORMS AND ANGLES.

In the writer's first work on variscite only four forms were determined, namely, *b*{010}, *a*{100}, *m*{110}, and *e*{012}. The study of additional crystals has extended this list to 14 forms, 9 new ones having been found on the 18 measured crystals and the presence of the base *c*{001} on crystals from Arkansas having been verified. The forms now established for variscite are as follows:

Pinacoids: *c*{001}, *b*{010}, *a*{100}.
Prisms: *l*{130}, *j*{250}, *d*{120}, *h*{340}, *m*{110}, *q*{210}, *f*{520}.
Domes: *e*{012}, *g*{032}, *t*{102}.
Pyramid: *p*{111}.

The average of the measured angles, as compared with the calculated values, is shown in the table below:

Measured and calculated angles for variscite.

[New forms are marked with a star.]

No.	Letter.	Symbol.	Number of crystals.	Number of measurements.	Measured.				Calculated.			
					φ		ρ		φ		ρ	
					°	′	°	′	°	′	°	′
1	*c*[a]	001	.....	.....	.....		.....		.....		0	00
2	*b*	010	18	22	0	00	90	00	0	00	90	00
3	*a*	100	5	5	90	00	90	00	90	00	90	00
4	**l*	130	4	6	20	30	90	00	20	26	90	00
5	**j*	250	3	4	24	08	90	00	24	06	90	00
6	**d*	120	3	3	29	20	90	00	29	12	90	00
7	**h*	340	2	2	40	10	90	00	39	59	90	00
8	*m*	110	18	45	48	13	90	00	48	12	90	00
9	**q*	210	1	2	65	51	90	00	65	54	90	00
10	**f*	520	2	4	70	10	90	00	70	19	90	00
11	*e*	012	18	30	0	00	28	35	0	00	28	38
12	**g*	032	6	12	0	00	58	22	0	00	58	36
13	**t*	102	1	1	90	07	31	54	90	00	31	24
14	**p*[b]	111	3	1	.....		.....		48	12	58	36

[a] The form *c*{001} not found on the crystals from Utah, is discussed on p. 79.
[b] The faces of *p*{111} were not measured by their coordinate angles. See p. 73.

c{001}. For description of the basal pinacoid, see p. 79. The form is not present on the crystals from Utah.

b{010}. The brachypinacoid *b* is the dominant form of variscite and is by far the largest form observed on all of the crystals. It is vertically striated, although on some crystals the striations are so faint as to be hardly discernible. The striations are strongly developed on the twin crystals.

a{100}. The macropinacoid *a*, a rare form, was seen on only five crystals, on all of which a single line face represented the form. The φ angle, theoretically 90° 00′, was measured as 89° 41′, 90° 05′, 90° 08′, 89°, 90° 08′.

m{110}. The unit prism is the second largest form on variscite. A faint vertical striation was noted on a few faces, whereas generally the faces of *m* are smooth and give good reflections. The measurements of the form have been already given.

The occurrences and measurements of the new prisms *l*, *j*, *d*, *h*, *q*, and *f* are given in the following table:

Occurrences and measurements of new prisms on variscite.

[Bold-faced figures show calculated values. Reflections poor. All line faces.]

Form and crystal No.	φ		Form and crystal No.	φ	
	°	′		°	′
l{230}	**20**	**26**	*h*{340}	**39**	**59**
1	19	08	1	40	29
2	21	24	2	39	52
3	21	12			
3	19	38	*q*{210}	**65**	**54**
3	20	34	2	65	50
15	21	05	2	65	51
j{250}	**24**	**06**	*f*{520}	**70**	**19**
1	24	06	13	69	42
1	24	08	13	69	26
12	25	23	13	71	13
13	22	55	16	70	17
d{120}	**29**	**12**			
1	29	37			
2	28	35			
16	29	49			

e{012}. The brachydome *e* is the third largest form on variscite and, with *m* and *b*, forms the combination of most of the crystals of the mineral. The measurements of *e* have already been given.

The new brachydome *g*{032} is very characteristic of the nearly square crystals, whose combination is *b*, *m*, *e*, *g*. On some crystals the faces of *g* are smaller than those of *e*; on other crystals they are much larger. The occurrences and measurements are shown below.

Occurrences and measurements of g{032}, variscite.

Crystal No.	Reflection.	Size of face.	ρ calculated 58° 36′.	
			°	′
4	Poor	Small	57	42
4	Poor	Medium	57	41
6	Fair	Medium	58	18
6	Fair	Medium	58	28
7	Poor	Line face	57	40
7	Fair	Medium	58	23
8	Poor	Small	58	10
9	Fair	Small	58	17

The new dome *t*{102} was observed only once, on crystal 1, as a medium-sized face giving a good reflection. It lay in the zone of and between *c*{001} and *a*{100}.

The unit pyramid *p*{111} was observed on three crystals as minute faces truncating the corners of the rectangular face of *b*{010}. It was measured on only one crystal, on which the angle *b*{010}: *p*{111} was found to be 55° 34′ (calculated 55° 20′). The unit pyramid was also observed under the microscope on several additional crystals which were obtained by crushing the coarsely granular mineral.

COMBINATIONS.

The combinations observed on the 18 measured crystals from Utah are shown in the table below.

Combinations on variscite crystals from Utah.

Letter.	Symbol.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
b	010	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*
a	100	*a*	....	*a*	....	*a*	....	....	....	....	....	*a*	....	....	....	*a*	....	....	....
l	130	*l*	*l*	*l*	....	....	....	....	....	....	....	....	....	....	....	*l*	....	....	....
j	250	*j*	....	....	....	....	....	....	....	....	....	....	*j*	*j*	....	....	....	....	....
d	120	*d*	*d*	....	....	....	....	....	....	....	....	....	....	....	....	....	*d*	....	....
h	340	*h*	*h*	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
m	110	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*	*m*
q	210	....	*q*	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
f	520	....	....	....	....	....	....	....	....	....	....	....	....	*f*	....	....	*f*	....	....
e	012	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*	*e*
g	032	....	....	....	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	....	....	....	....	....	....	....
t	102	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	*t*	....	....
p	111	....	....	....	....	*p*	....	*p*	*p*	....	....	....	....	....	....	....	....	....	....

ZONAL RELATIONS.

The zonal relations of variscite can be seen on the accompanying gnomonic projection (fig. 62, p. 74), which is to be compared with the projection of lucinite forms shown in figure 54 (p. 62). The prism zone is by far the richest, as it contains 9 out of a total of 14 forms. The other three zones are: *c e g b*, *c t a*, *c p m*.

HABITS.

All the crystals examined are more or less tabular in habit, but several modifications were noted, as described below.

Very thin, elongated plates, tabular parallel to *b*{010}.
Short prismatic crystals.
Stout prismatic, nearly equidimensional crystals.
Long prismatic crystals.
Stout rectangular plates.

Very thin, elongated plates, tabular parallel to *b*{010}, are abundant on some of the specimens. A simple combination, *b m e*, is shown in

figure 63, whereas a somewhat thicker crystal with a richer combination is shown in figure 64. A much stouter tabular crystal, intermediate between the very thin plates and the short prismatic crystals, is shown in figure 65.

Other crystals are much stouter than the one shown in figure 65, and these crystals are also much shorter, so that their habit may be

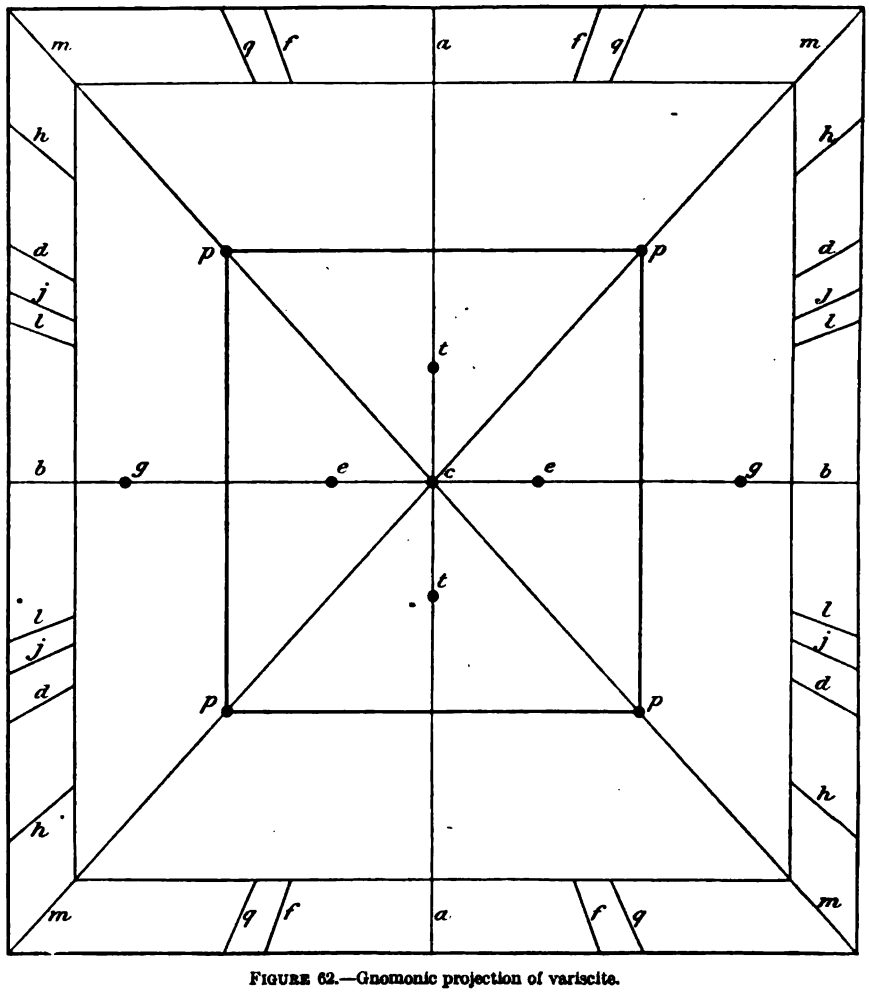

FIGURE 62.—Gnomonic projection of variscite.

described as short prismatic. The combination observed on crystals of this habit is always *b m e*. The variation in habit of the short prismatic crystals to the stout prismatic, nearly equidimensional crystals is shown in figures 66 and 67.

The stout prismatic, nearly equidimensional crystals (fig. 67) are rather rare, but such habits as are illustrated in figures 63 to 66 are much more common.

On a few specimens were noticed long prismatic crystals, similar in combination to those shown in figures 66 and 67, except that they

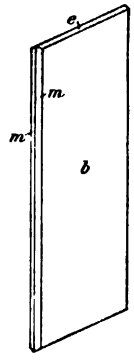

FIGURE 63.

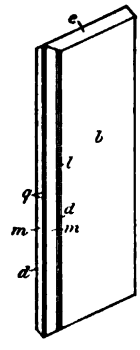

FIGURE 64.

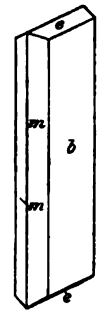

FIGURE 65.

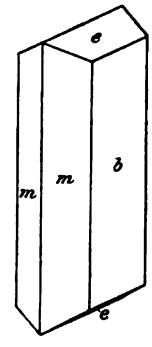

FIGURE 66.

FIGURE 63.—Very thin, elongated plates of variscite, tabulated parallel to $b\{010\}$. Forms: $b\{010\}$, $m\{110\}$, $e\{012\}$.

FIGURE 64.—A thicker crystal of variscite with a richer combination. Forms: $b\{010\}$, $l\{130\}$, $d\{120\}$, $m\{110\}$, $q\{210\}$, $e\{012\}$.

FIGURE 65.—A much stouter, tabular crystal of variscite. Forms: $b\{010\}$, $m\{110\}$, $e\{012\}$.

FIGURE 66.—Short prismatic habit of crystal of variscite. Forms: $b\{010\}$, $m\{110\}$, $e\{012\}$.

are elongated parallel to the vertical axis. Such a long prismatic crystal is shown in figure 68.

A very few crystals of a short to stout prismatic habit showed large development of the new brachydome $g\{032\}$, as shown in figure

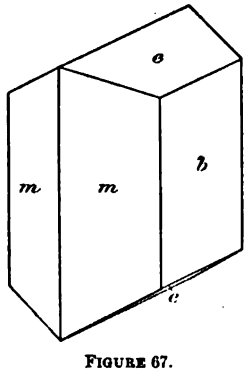

FIGURE 67.

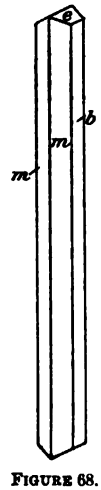

FIGURE 68.

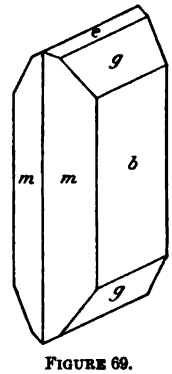

FIGURE 69.

FIGURE 67.—Stout prismatic, nearly equidimensional crystal of variscite.

FIGURE 68.—Long prismatic crystal of variscite.

FIGURE 69.—Short prismatic crystal of variscite with new dome. Forms: $b\{010\}$, $m\{110\}$, $e\{012\}$, $g\{023\}$.

69, and serve as a connecting link between the prismatic tabular crystals (figs. 63 to 66) and the stout rectangular plates (figs. 70 to 72).

figure 63, whereas a somewhat thicker crystal with a richer combination is shown in figure 64. A much stouter tabular crystal, intermediate between the very thin plates and the short prismatic crystals, is shown in figure 65.

Other crystals are much stouter than the one shown in figure 65, and these crystals are also much shorter, so that their habit may be

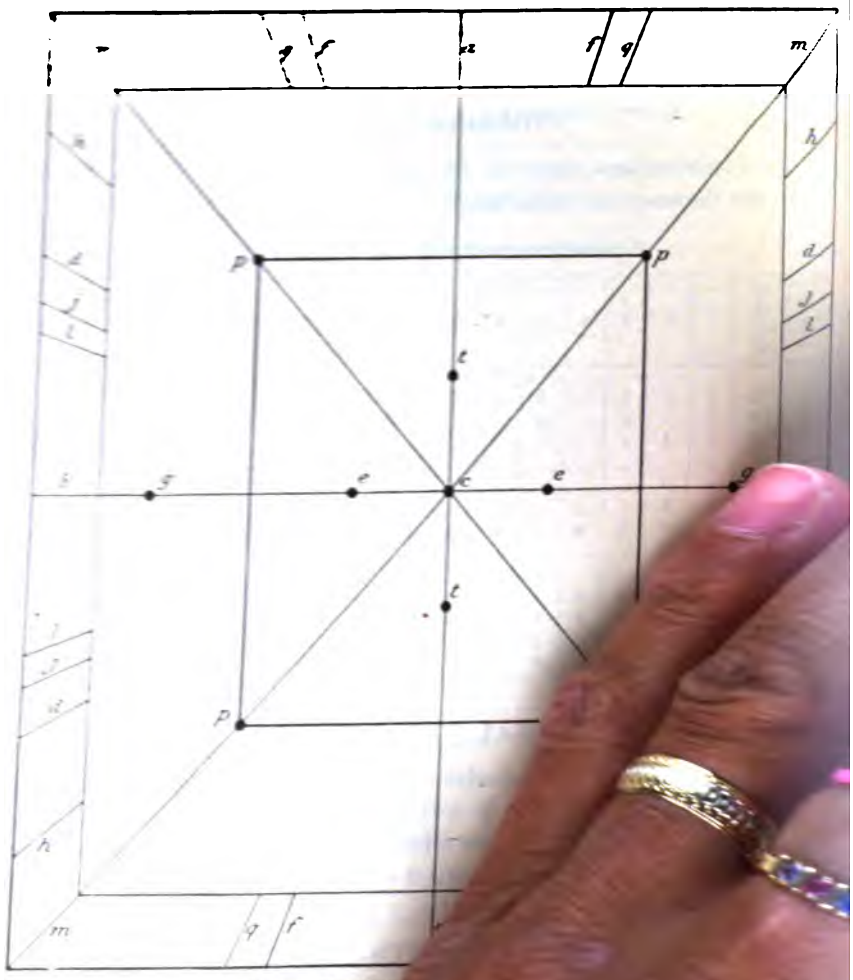

FIGURE 62.—Gnom

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On a few specimens were noticed long prismatic crystals, similar in combination to those shown in figures 66 and 67, except that they

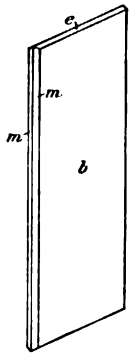

FIGURE 63.

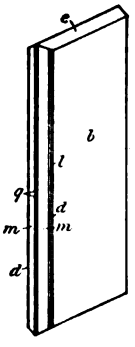

FIGURE 64.

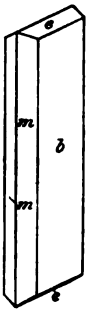

FIGURE 65.

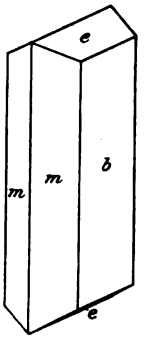

FIGURE 66.

FIGURE 63.—Very thin, elongated plates of variscite, tabulated parallel to *b*{010}. Forms: *b*{010}, *m*{110}, *e*{012}.

FIGURE 64.—A thicker crystal of variscite with a richer combination. Forms: *b*{010}, *l*{130}, *d*{120}. *m*{110}, *g*{210}, *e*{012}.

FIGURE 65.—A much stouter, tabular crystal of variscite. Forms: *b*{010}, *m*{110}, *e*{012}.

FIGURE 66.—S[illegible]smatic habit of crystal of variscite. Forms: *b*{010}, *m*{110}, *e*{012}.

are elo[illegible]rallel to the [illegible] axis. Such a long prismatic crystal [illegible] in figure 68.

[illegible] rystals of a [illegible]out prismatic habit showed [illegible]nt of the n[illegible]me *g*{032}, as shown in figure

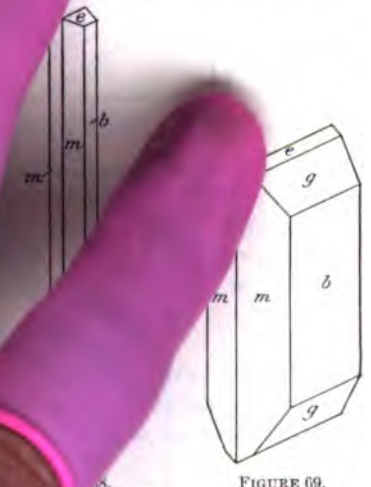

FIGURE 69.

[illegible]tal of variscite.

[illegible] new dome. Forms: *b*{010}, *m*{110}, *e*{012}, *g*{023}.

[illegible]nk between the prismatic tabular [illegible] stout rectangular plates (figs. 70

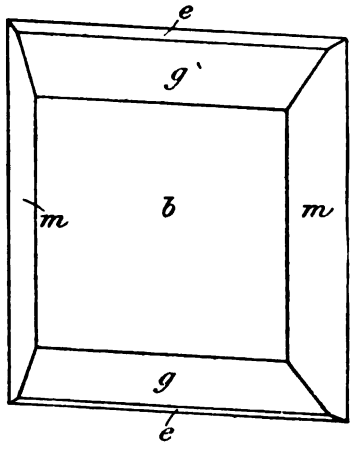

FIGURE 70.

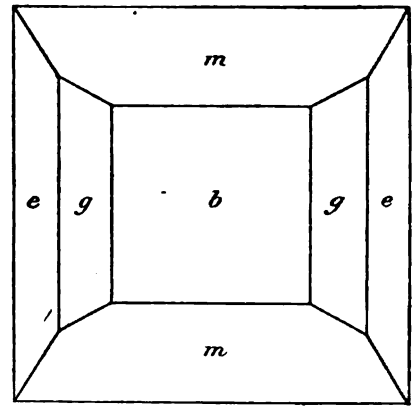

FIGURE 71.

FIGURE 70.—Clinographic projection of a stout rectangular crystal of variscite, with $b\{010\}$ drawn in front. Forms: $b\{010\}$, $m\{110\}$, $e\{012\}$, $g\{023\}$.

FIGURE 71.—Orthographic projection on $b\{010\}$ of a stout rectangular crystal of variscite. Same forms as in figure 70.

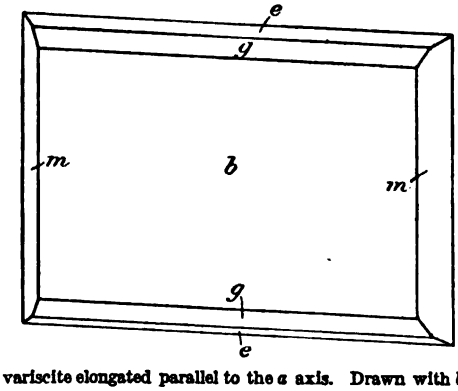

FIGURE 72.—Crystal of variscite elongated parallel to the a axis. Drawn with $b\{010\}$ in front. Forms: $b\{010\}$, $m\{110\}$, $e\{012\}$, $g\{023\}$.

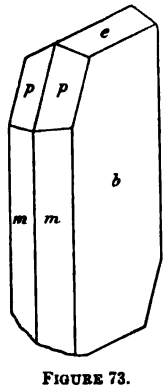

FIGURE 73.

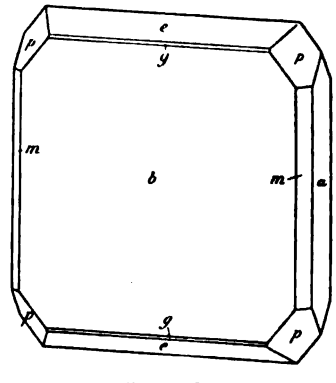

FIGURE 74.

FIGURE 73.—Short prismatic crystal of variscite, with faces of $p\{111\}$.

FIGURE 74.—Stout rectangular crystal of variscite (No. 5), drawn with $b\{010\}$ in front. Forms: $b\{010\}$, $a\{100\}$, $m\{110\}$, $e\{012\}$, $g\{023\}$, $p\{111\}$.

The stout rectangular plates, nearly as wide as high, are abundant on a few specimens, but do not occur directly with the prismatic forms. The combination of these stout rectangular plates is essentially *b m e g;* rarely a line face of *a*{100} or a minute face of *p*{111} is also present. A clinographic projection of such a stout rectangular crystal, drawn with the brachypinacoid *b*{010} in front, is shown in figure 70. A similar crystal, in orthographic projection on *b*{010}, is shown in figure 71, in which the relative sizes of the four forms *b*, *m*, *g*, and *e* can be well seen.

An extreme case, in which the crystal is elongated parallel to the *a* axis, is shown in figure 72. Only one such crystal was noted. Figure 73 represents a crystal observed under the microscope. It has a short prismatic habit and is noteworthy for the large develop-

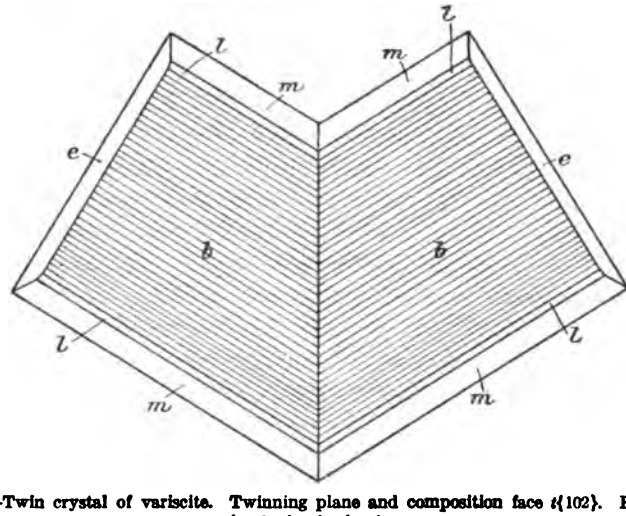

FIGURE 75.—Twin crystal of variscite. Twinning plane and composition face *t*{102}. Forms: *b*{010}, *m*{110}, *l*{120}, *e*{012}.

ment of faces of the unit pyramid *p*{111} which are unequally developed in their size, for the rear upper faces are very small.

A stout rectangular crystal with well-developed small faces of *p*{111} is shown in figure 74, with *b*{010} drawn in front.

TWINNING.

Twinning is by no means rare for the crystals of variscite, and several such twins have been measured. The prism zone is generally well developed on these twins, and several prisms, notably *l*{120}, are to be found on them in addition to *m*{110}.

The twinning plane is *t*{102}, and all the twins seen are contact twins with the twinning plane as the composition face. Such twins have been observed previously under the microscope, but on the present material they occur in measurable crystals. A contact twin of variscite is shown in figure 75, with the twinning plane {102} vertical.

RELATION TO VARISCITE CRYSTALS FROM ARKANSAS.

The crystals of variscite from Arkansas were described in 1878 by Chester,[1] whose crystal drawing is here reproduced as figure 76. Chester describes these crystals as follows:

The crystals are rarely distinct but are usually found in complicated groups, sometimes forming clusters of a sheaf form. Very rarely single prismatic crystals are found, sufficiently distinct to admit of measurement. Figure 1 [fig. 76] gives the most common form, belonging to the orthorhombic system, and showing faces of *I* [*m*{110}], *ii* [*a*{100}], *ii* [*b*{010}], and *O* [*c*{001}]. In this crystal *I*:*I*=114° 6′. In general but one termination is seen, but crystals showing both ends are sometimes found lying on the quartz matrix, the bases being similar to each other. The face *ii* [*a*{100}] is very small and therefore easily overlooked, and *ii* [*b*{010}] is about the same size as *I*, so that these crystals may readily be mistaken for hexagonal prisms. Crystals showing a simple termination like that in figure 1 [fig. 76] are seldom seen. More frequently the basal plane is * * * more complicated. These planes are often covered with a thin opaque white coating, probably of quartz.

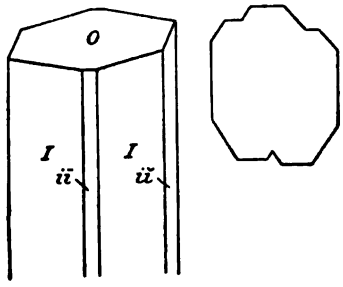

FIGURE 76.—Crystal of variscite from Arkansas. (After A. H. Chester.) The interpretation of the forms, after Chester, is O={001}, I={110}, ii={100}, ii={010}. Probably a more correct interpretation is to make I={210}.

Although Chester does not mention any striations on his prismatic crystals, yet the "sheaf forms" composed of "prismatic crystals" would indicate a vertical striation in the prism zone. From the angle (110): (110)=114° 06′, as given by Chester, the angle of a pinacoid to the unit prism is 57° 03′. An attempt to correlate this angle with an angle on the Utah variscite or lucinite has not led to any conclusive correlation, as shown in the table below.

Comparison of angles of variscite.

Arkansas variscite measured by Chester.	Utah variscite.	Utah lucinite.
° ′	° ′	° ′
(010) : (110)=32 57	(010) : (130)=20 26	
(010) : (110)=57 03	(010) : (250)=24 06	
	(010) : (120)=29 12	(010) : (120)=29 48
	(010) : (340)=39 59	
	(010) : (110)=48 12	(010) : (110)=48 53
	(010) : (210)=65 54	(010) : (210)=66 25
	(010) : (520)=70 19	

The only form of Utah variscite which approaches in angular value the measurement of Chester (32° 57′) is *d*{120}, whose ϕ angle, 29° 12′, is 3° 45′ less. Chester makes the statement that the

[1] Chester, A. H., Note on the crystallization of variscite: Am. Jour. Sci., 3d ser., vol. 15, p. 207, 1878.

faces of $b\{010\}$ and $m\{110\}$ are of about the same size, and it seems not impossible that the angle Chester measured is not, as he gives it, prism to prism, $m : m$, but brachypinacoid to prism, $b : m$, or (010) : (110). If this is true, his measurement, 114° 06′ or 65° 54′, is identical with the angle (010) : (210) = 65° 54′ of the Utah variscite. It seems probable, therefore, that Chester's unit prism is in reality the prism (210), for with this change the Arkansas variscite becomes identical in angular value with the Utah variscite.

The question still remains whether the basal pinacoid, O of Chester, is in reality a distinct form or only a coalescence of numerous non-parallel faces of some other form or forms.

The collection of the late Albert F. Holden, which is now in the Mineralogical Museum of Harvard University, contains several specimens of the Arkansas variscite which on visual inspection seemed to possess measurable crystals. Through the kind permission of Mr. Holden several of the crystals were detached and measured. It was soon found, however, that nearly all the crystals consisted of barrel-like or sheaf-like groupings of numerous crystals, hardly any two of which were in parallel position. Finally a crystal was found that allowed approximate measurement, with the following result. The crystal was not a single unit, but was built up of several in nearly parallel position. The faces being defined by their size, the measurements may be given as follows: What is here described as a face, however, consists of numerous faces in approximate parallel position, the reflections of which varied several degrees from one another. The measured angle represents the center of these masses of reflections.

Measurement of prism zone of variscite from Arkansas.

Angle.		Interpretation.		
		Form.	Calculated angle.	
	°		°	′
From first large face (100) to next small face	57	120	60	48
To next medium face	29	010	29	12
To next small face	33	$\bar{1}20$	29	12
To next large face	58	$\bar{1}00$	60	48
To next small face	61	$\bar{1}\bar{2}0$	60	48
To next medium face	29	$0\bar{1}0$	29	12
To next small face		$(1\bar{2}0)$	.....	
Back to first	93	100	90	00

If the interpretation above set forth is correct, then the prism forms on the crystal measured are $b\{010\}$, $a\{100\}$, and $d\{120\}$, whereas, according to the interpretation here given of Chester's measurements,

the combination in the prism zone on his crystal was $b\{010\}$, $a\{100\}$, $q\{210\}$. The coincidence of the first measured angle (57°) with Chester's measurement (57° 03′) is more apparent than real, for the different values of the same angle as measured on the crystal here described are 57°, 61°, 57°, 62°, 61°, average 59° 50′.

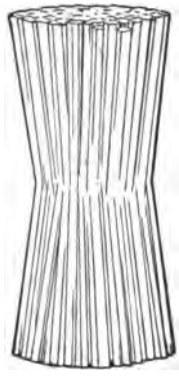

FIGURE 77.—Crystal of variscite from Arkansas, showing sheaf-like structure. The forms present are probably: $c\{001\}$, $b\{010\}$, $a\{100\}$, $d\{120\}$.

Although the base was convexly rounded, the series of reflections ceased at a ρ angle of 17° on one side and 14° on the other—that is, the outermost reflecting face on one side of the base was inclined about 17° to the main axis of the composite crystal, and the outermost reflecting surface on the other side of the base was inclined about 14° from the main axis. The crystal can readily be seen to have a sheaf form, as shown in figure 77, and as the known forms nearest to the base are inclined thereto at considerably more than 17°—(001) : (102) = 31° 24′; (001) : (012) = 28° 38′—it is concluded that the terminal face is in reality the basal pinacoid. The form $c\{001\}$ must therefore be included in the form system of variscite.

The approximate appearance of one of these sheaf-like crystals, with the interpretation of the forms as deduced from the measurements, is shown in figure 77.

SCHNEEBERGITE.

ORIGIN OF INVESTIGATION.

Schneebergite, which was incompletely described in 1880 by its discoverer, was considered to be closely related to atopite until Eakle and Muthmann [1] in 1895 put it in the garnet group. Koechlin in 1901 showed that such a conclusion was not correct, and the true status of schneebergite has remained in uncertainty ever since.

When the writer was in Vienna in 1912 Dr. Koechlin brought out the specimens of schneebergite and readily agreed to furnish the material for a reexamination of the mineral. With his customary liberality he sent his entire collection of specimens to Washington, where they were studied as time afforded. Hearty thanks are due to Dr. Koechlin for his willingness to sacrifice his valuable material in order to have the properties of schneebergite determined.

The results obtained may be briefly summarized as follows: Schneebergite is an isometric mineral crystallizing in octahedra which show anomalous double refraction. Chemically it is an iron-calcium-antimony compound, of the empirical formula $CaSbO_3$. The antimony exists in two states of oxidation, and the formula, written $2CaO.Sb_2O_4$, is interpreted as $2CaO.Sb_2O_3+2CaO.Sb_2O_5$. Although related to romeite and atopite, it is very distinct from them and forms a well-characterized, definite mineral species. In order to correlate schneebergite with the other known calcium antimonates, it became necessary to investigate also romeite and atopite, and the results obtained are stated in the following paper. For comparative purposes it may be stated here that in romeite the antimony does not exist in two states of oxidation as given by Damour but only in the higher state. The formula for romeite is $5CaO.3Sb_2O_5$. The formula for atopite, based only on Nordenskiöld's analysis, is $2CaO.Sb_2O_5$. The Brazilian so-called atopite is romeite. Possibly the Swedish atopite is the same as romeite.

Although some of the writers who have described schneebergite confused that mineral with garnet and gave therefore not a description of schneebergite but of garnet, the results obtained by them are of interest and value and have been abstracted at some length, especially the descriptions of the paragenesis. The following historical sketch is thereby somewhat extended, but the facts already published are best given in one section and can then be conveniently referred to as a whole.

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[1] See page 85 for bibliography.

HISTORICAL SKETCH.

Schneebergite was first described by Brezina in 1880. It was found at the Pockleithner-Halde, Schneeberg, Tyrol, Austria, in transparent honey-yellow octahedra, which had a vitreous to adamantine luster. The average of nine measurements of the octahedral angle was 70° 31.9′ (calculated 70° 31.7′), the limits being 70° 26.5′ and 70° 36.6′. The small octahedra, ranging in size from 0.5 to 1 millimeter, occurred isolated in anhydrite, gypsum, or chalcopyrite. The mineral also formed layers in the chalcopyrite. Other associated minerals were magnetite, sphalerite, and pyrrhotite. Many of the octahedra of schneebergite had microscopic inclusions of magnetite or of negative crystals, and the mineral was then birefringent; otherwise it was isotropic. The crystals were brittle with a conchoidal fracture and showed traces of a cleavage after {110}. The hardness is 6.5. The density was determined on 0.17 gram as 4.1 (average of 3.9, 4.1, 4.3). When heated before the blowpipe, the crystals turned slightly brown but did not fuse. Long-continued fusion with sodium carbonate finally dissolved them. Qualitative tests showed the presence of much antimony and lime, a small amount of iron, and traces of copper, bismuth, zinc, magnesia, and sulphuric acid.

The material studied by Elterlein, who was the second writer on schneebergite, was similar to that used by Brezina, except that calcite and breunnerite took the place of anhydrite and the schneebergite occurred not as individual crystals, but only as a crystalline aggregate, in part in reniform masses. Most of Elterlein's schneebergite was garnet. The paragenesis of the ores of Schneeberg are given in detail by Elterlein, and the following paragraphs contain notes taken from his description.

The chief ore at Schneeberg is a massive, mostly deep-black sphalerite, which occurs either in pure masses or in intimate mixture with one or more of the other materials, particularly with breunnerite and quartz, but also with tremolite (called Strahlstein in German), galena, garnet, etc. Galena is the second most abundant ore mineral, followed by pyrite, chalcopyrite, magnetite, pyrrhotite, boulangerite, tetrahedrite, and others. The chief nonmetallic minerals are quartz, breunnerite, and calcite. The general succession of minerals in the ore veins of Schneeberg is given as (1) quartz, (2) sulphides, (3) carbonates. In more detail, the order of succession is given as quartz, sphalerite (rarely pyrite or breunnerite), breunnerite (rarely galena), galena.

In addition to the above-named minerals, the following have been found in the Schneeberg veins: Silver, greenockite, arsenopyrite, argentite, ilmenite, brown iron ore, fluorite, dolomite, goslarite, malachite, gypsum, schneebergite, apatite, almandite, biotite, muscovite, and chlorite.

Out of the 39 mineral successions given by Elterlein, schneebergite is given in only one, No. 20, which is (1) breunnerite, (2) schneebergite, granular [doubtless garnet and not schneebergite]. He also claims to have traced under the microscope the alteration of calcite and breunnerite into schneebergite and in fact considers the breunnerite as the mother mineral of schneebergite [doubtless garnet]. He also remarks that garnet correspondingly disappears as the breunnerite increases in amount. Elterlein describes the garnet as red and showing either {110} or {110} with {211}, and his garnet is a different variety from what he called schneebergite. As will be pointed out later, what Elterlein called schneebergite was in fact garnet. The view is supported by the fact that the analysis of Eakle and Muthmann was made on material from a series of specimens collected by Elterlein.

Many of the ore veins, as figured by Elterlein, consist of parallel even layers of pure quartz, sphalerite, galena, or pyrite, or of mixtures of these with other minerals. Other occurrences show a concentric filling of open spaces (fig. 79, p. 86) with the same minerals, and many of the specimens of schneebergite at the writer's disposal show a concentric arrangement of the mineral layers. (Compare figs. 78 and 80.)

The material analyzed by Eakle and Muthmann is described by them as follows:

> Most of the mineral appears as crystalline aggregates upon the ore, which latter consists of a mixture of magnetite, zinc blende, and chalcopyrite; the gangue mineral is massive quartz. The aggregates are partly kidney shaped and consist of rounded crystal grains, with scarcely recognizable form. The color varies from honey-yellow to bright wine-yellow; the surface is often brown from a slight decomposition, the color being due to a thin coating of iron hydroxide. The perfectly fresh, undecomposed crystals are isotropic and occasionally show weak and abnormal double refraction, especially when they contain inclusions of fine particles of the ore.
>
> On other ore specimens the mineral appears as thin coatings or as a deposit; occasionally well-defined crystals can be observed, all of which show the single form of the octahedron. The crystals are generally accompanied by calcite and breunnerite, from which the mineral has evidently originated, as has been shown by v. Elterlein; commonly the schneebergite surrounds the calcite, if it has not entirely replaced it. The paragenesis can be followed still better in sections under the microscope. It can be seen that the calcium-iron carbonate changes at first to a light-yellow double-refracting mineral of indefinite composition, which by further change becomes granular and isotropic and finally passes into the pure schneebergite.

The description of what Elterlein calls schneebergite is so similar to that of the material analyzed by Eakle and Muthmann (and found to be garnet) that there can be no question that what Elterlein called schneebergite was in reality a garnet. Eakle and Muthmann found the density of their material to be 3.838. In a blast flame it fused to a dark-brown liquid, whereas Brezina describes schneebergite as

infusible. The analysis of Eakle and Muthmann showed their material to be a pure lime-iron garnet.

Analysis of garnet (supposed to be schneebergite).

[Eakle and Muthmann, analysts.]

	Found.		Calculated for $3CaO.Fe_2O_3.3SiO_2$.
	1	2	
SiO_2	.....	35.45	35.43
Fe_2O_3	32.33	32.11	31.50
CaO	32.58	.....	33.07

The facts which indicate that Elterlein and also Eakle and Muthmann confused garnet with schneebergite are briefly summarized as follows:

1. Elterlein's succession No. 20—(1) breunnerite, (2) schneebergite, which should read (1) breunnerite, (2) garnet—was observed by the writer on many specimens (figs. 83 and 84).

2. The alteration of breunnerite to schneebergite as described by Elterlein and by Eakle and Muthmann could not be found by the writer, whereas the derivation of garnet from breunnerite is common.

3. The reciprocal abundance of red dodecahedral garnet and breunnerite, as noted by Elterlein, suggests the derivation of garnet from the carbonate mineral and makes the view plausible that the yellow octahedral garnet (the so-called schneebergite) may also have been derived from breunnerite.

4. Elterlein's garnets showed only {110} and {211}. Therefore he did not recognize the presence of octahedral garnet and took such a rare form of garnet to be schneebergite.

5. The specimens in Munich, which furnished the material on which Eakle and Muthmann made their analysis, were originally collected by Elterlein and doubtless formed in part the basis of his own description.

As a result of the analysis given by Eakle and Muthmann, schneebergite was considered as a garnet and was included as such in the textbooks of mineralogy. In 1902 Koechlin reviewed the history of schneebergite and, after pointing out some inconsistencies between the results obtained by Eakle and Muthmann and those given by Brezina, gave the results of his own interrupted investigation of the mineral. Koechlin quotes a letter from Fr. Löffler, who said that schneebergite occurred in anhydrite only in the first specimens found. Moreover, anhydrite and gypsum have been found only rarely. Most of the specimens were obtained from the dump, and

those most likely to contain schneebergite consist of drusy sphalerite, which contains also pyrite, chalcopyrite, ankerite (the breunnerite of Elterlein), or calcite. The druse was coated with secondary calcite which, when removed with acid, showed the schneebergite crystals. Koechlin found schneebergite on about a quarter of the specimens supplied by Löffler; the others show only the garnet of Eakle and Muthmann.

A distinct succession was observed by Koechlin as follows: The lower part of the specimens consists of pure sphalerite. Next follows a layer consisting chiefly of breunnerite and calcite, but containing also quartz, tremolite, sphalerite, chalcopyrite, and magnetite. In this layer occurs also the garnet. Above this is a layer in which magnetite and chalcopyrite predominate, but the carbonates are hardly visible. Toward the upper portion of this layer the sulphides are drusy, and on this drusy layer and embedded therein is the true schneebergite. The layer of secondary calcite which originally coated the schneebergite had been completely removed by acid when the specimens were received by Koechlin. The schneebergite was therefore the next to the last mineral to form in the "Hohlraumausfüllungen mit concentrischkrustenförmiger Textur," which are abundant in the veins at Schneeberg. The schneebergite was never seen in the lower layers or bands.

Koechlin made a partial analysis of schneebergite, with the following result: CaO, 20.14 per cent, 19.91 per cent; Fe_2O_3, 8.48 per cent; MgO, 0.18 per cent; traces of bismuth, alumina, potassium, sodium, arsenic, tin, and lead. Silica, copper, zinc, and sulphuric acid were absent. Moreover, antimony, though not quantitatively determined, was found to be present in large amount.

A determination of the refractive index of schneebergite gave Hlawatsch the result $n=2.10$, thereby confirming the work of Koechlin and disposing of the erroneous conclusion that schneebergite was only a lime-iron garnet.

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The following is a list of the publications cited discussing schneebergite:

BREZINA, A., Ueber ein neues Mineral, den Schneebergit: K. k. geol. Reichsanstalt Wien Verh., 1880, p. 313.

ELTERLEIN, A. VON, Beiträge zur Kenntniss der Erzlagerstätte des Schneebergs bei Mayrn in Südtirol: K. k. geol. Reichsanstalt Wien Jahrb., vol. 41, p. 289, 1891.

EAKLE, A. S., and MUTHMANN, W., Ueber den sogenannten Schneebergit: Zeitschr. Kryst. Min., vol. 24, p. 581, 1895; Am. Jour. Sci., 3d ser., vol. 50, p. 244, 1895.

KOECHLIN, R., Zur Schneebergitfrage: Min. pet. Mitt., vol. 21, p. 15, 1902.

HLAWATSCH, C., Der Brechungsexponent des Schneebergits: Min. pet. Mitt., vol. 21, p. 21, 1902.

PARAGENESIS.

The following descriptions of the paragenesis of schneebergite are based entirely on the specimens obtained from Dr. Koechlin. No data are available to indicate the relation of the specimens to the vein or rock of the region. The descriptions apply therefore only to the specimens themselves.

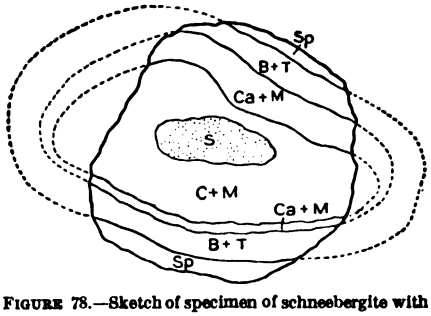


FIGURE 78.—Sketch of specimen of schneebergite with concentric bands. Compare figure 79. S, Schneebergite; C, chalcopyrite; M, magnetite; Ca, calcite; B, breunnerite; T, tetrahedrite; Sp, sphalerite.

A very marked feature of nearly all the specimens is a distinct banding. The bands are nearly parallel on some specimens and decidedly concentric on others. The parallel bands, in fact, may be only apparently parallel and may be part of an elongated concentric structure. One specimen in particular had an ellipsoidal arrangement of the bands, as is shown diagrammatically in figure 78. Elterlein describes the occurrence of "concentrischkrustenförmige Textur" in the "Hohlraumausfüllungen," and the structure of the specimen, as shown in figure 78, shows this same concentric arrangement of the cavity filling. According to Elterlein many of these lens-shaped bodies are built up of alternating layers of breunnerite and of galena. Figure 79 is a copy of Elterlein's sketch illustrating this relation. It is believed that the specimens of schneebergite represent similar "filling in" of cavities, although the concentric structure is not well shown on most of the specimens. It is to be remarked, however, that many small specimens from a filled-in cavity of the shape shown in figure 79 could be obtained that would show only parallel bands in which the concentric structure would be lost.

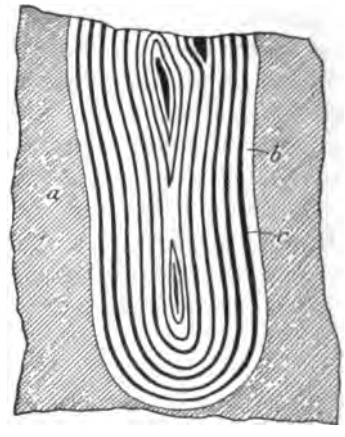


FIGURE 79.—A lens-shaped cavity in sphalerite (*a*) filled in by alternating layers of breunnerite (*b*) and galena (*c*). One-fourth natural size. (After Elterlein.) Compare with figure 78.

Two other specimens also show well the concentric arrangement of the bands and are sketched in figures 80 and 81. A part of the original calcite covering the schneebergite still remains on the specimen shown in figure 80. The presence of two small bodies of garnet (shown in solid black in fig. 80), one of them completely embedded in the schneebergite, is anomalous, but there is

no reason why a secondary mineral like this garnet should not migrate and finally be deposited wherever conditions were favorable. The specimen illustrated in figure 80 is the only one ever seen by Dr. Koechlin that shows the direct association of garnet with schneebergite.

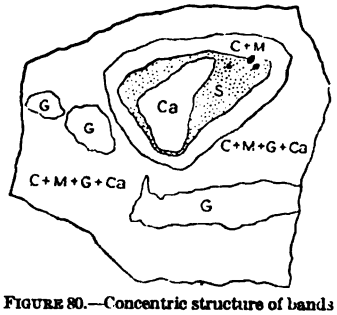


FIGURE 80.—Concentric structure of bands of minerals on specimen of schneebergite. C, Chalcopyrite; M, magnetite; S, schneebergite; G, garnet; Ca, calcite. Solid black, garnet embedded in schneebergite.

Figure 81 represents a portion of a specimen so broken as to show the granular calcite, which has been removed on most of the specimens.

Four specimens show the associations of schneebergite very well and are therefore briefly described. They are illustrated in Plate III, *A*, *B*, *C*, and Plate IV, *B*. Figures 82, 83, 84, and 86 give the necessary explanation.

Plate III, *A*, shows a small specimen which has four distinct bands—a lower band containing a mixture of quartz and sphalerite, then magnetite with inclosed nodular masses of garnet, a thin layer of white calcite, and on top an aggregate of chalcopyrite and magnetite. On the upper surface of this aggregate isolated crystals of schneebergite are to be found. No chalcopyrite is present in the bands below the chalcopyrite and magnetite mixture but galena in small specks is scattered through all the bands except the lower one.

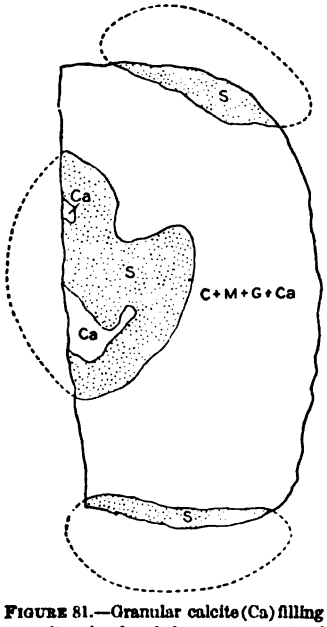


FIGURE 81.—Granular calcite (Ca) filling cavity in banded arrangement of schneebergite (S) and associated minerals. C, Chalcopyrite; M, magnetite; G, garnet.

The specimen illustrated in Plate III, *B*, is very rich in schneebergite, and the material used for the chemical analysis was in part obtained from the left-hand corner of the upper layer of this specimen. The lower portion of the specimen is an aggregate of chalcopyrite and garnet in which are two large remnants of breunnerite (mixed with chalcopyrite). Above this is an aggregate of chalcopyrite and magnetite which is somewhat porous in its upper part, and it is here that an abundant schneebergite is found, intimately mixed with the chalcopyrite and magnetite.

Plate III, *C*, shows the following succession of minerals: The lower portion, a little less than half of the specimen, is quartz, above which is an irregular band of breunnerite. Isolated masses of quartz occur in the breunnerite, and breunnerite is also found as inclusions in the quartz. An incomplete small band of magnetite lies partly between the breunnerite and quartz and partly in the breunnerite. Above this is a black layer of calcite and magnetite, which is followed by a layer of white calcite. The bands of breunnerite, calcite, and magnetite, with included small quartz masses, do not show sharp boundaries, but grade into one another. Several nodular masses of garnet are inclosed in this series of bands. Chalcopyrite is also scattered irregularly through these bands. Above these bands, but not sharply separated from the white calcite, is a layer of chalcopyrite and magnetite containing schneebergite in its upper portion.

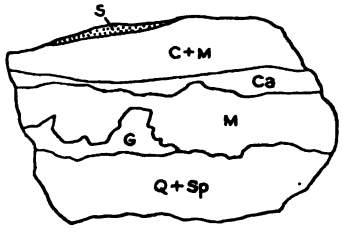


FIGURE 82.—Diagram of specimen shown in Plate III, *A*. Sp, Sphalerite; Q, quartz; G, garnet; M, magnetite; Ca, calcite; C, chalcopyrite; S, schneebergite.

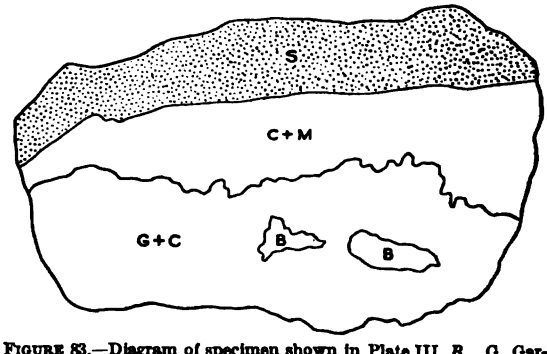


FIGURE 83.—Diagram of specimen shown in Plate III, *B*. G, Garnet; C, chalcopyrite; B, breunnerite; M, magnetite; S, schneebergite

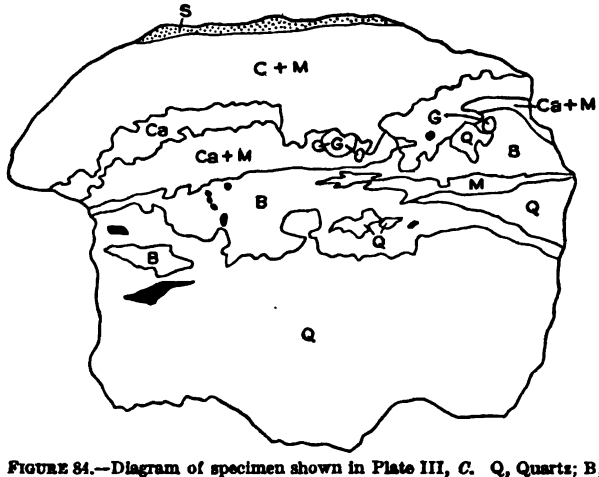
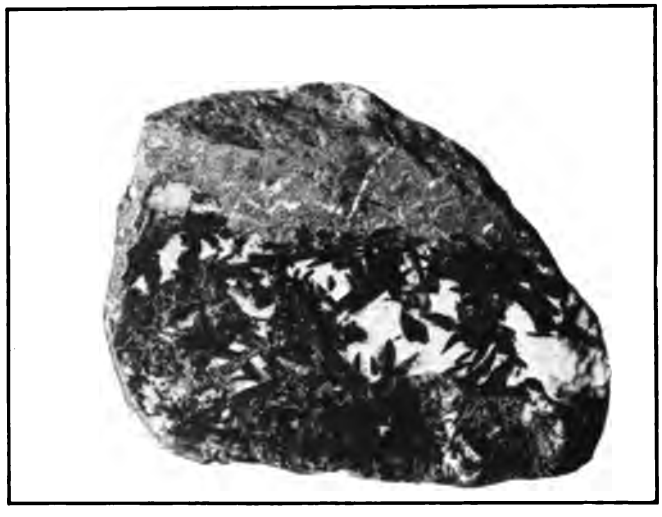


FIGURE 84.—Diagram of specimen shown in Plate III, *C*. Q, Quartz; B, breunnerite; M, magnetite; G, garnet; Ca, calcite; C, chalcopyrite; S, schneebergite; solid blank, galena.

In the specimen pictured in Plate IV, *B*, massive black sphalerite forms the lower third. Above it lies a broad band composed essentially of a mixture of sphalerite, galena, magnetite, and breunnerite. Some tremolite is also present. An irregular narrow band of magnetite overlies this broad band and is in turn followed by one of quartz or quartz and breunnerite. A band

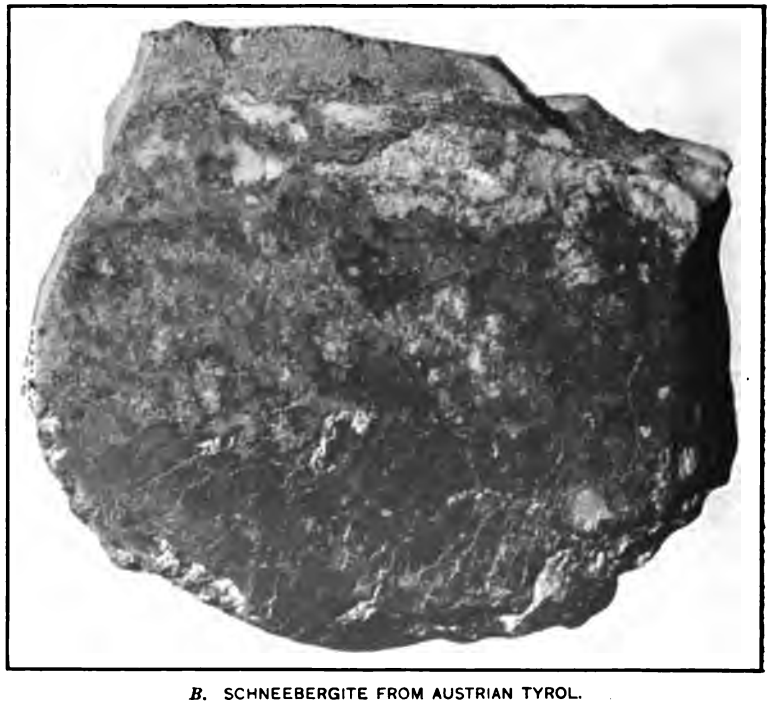
ORE SPECIMENS WITH SCHNEEBERGITE FROM SCHNEEBERG, AUSTRIAN TYROL.

For explanation see figures 82 to 84. All natural size.



A. ROMEITE FROM ITALY.

For explanation see figure 85. Natural size. Described on page 96.



B. SCHNEEBERGITE FROM AUSTRIAN TYROL.

For explanation see figure 86. Natural size.

of calcite and magnetite comes next, and over it is a mixture of chalcopyrite and magnetite containing schneebergite in its upper portion. No garnets were seen on this specimen, but they may well be present, especially in the band of quartz and breunnerite. No chalcopyrite occurs below the upper layer, but galena is scattered throughout the specimen.

The succession of minerals on the schneebergite specimens as described and illustrated in Plates III and IV and figures 82, 83, 84, and 86 may be summarized as follows:

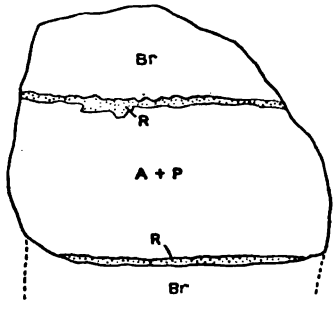


FIGURE 85.

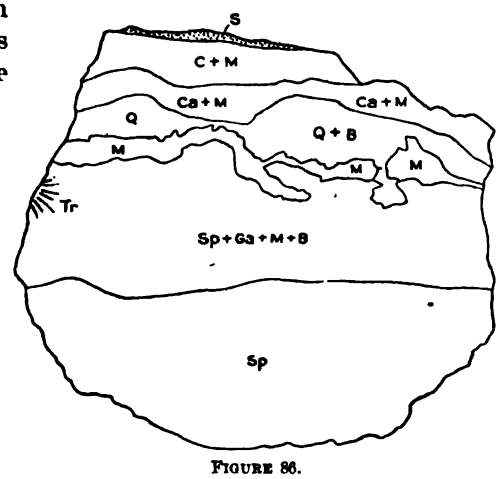


FIGURE 86.

FIGURE 85.—Diagram of specimen shown in Plate IV, *A*. Described on page 96. Br, Braunite; R, romeite; A+P, albite and piedmontite.

FIGURE 86.—Diagram of specimen shown in Plate IV, *B*. Sp, Sphalerite; Ga, galena; M, magnetite, B, breunnerite; Tr, tremolite; Q, quartz; Ca, calcite; S, schneebergite.

Succession of minerals on specimens of schneebergite.

	Pl. III, *A*.	Pl. III, *B*.	Pl. III, *C*.	Pl. IV, *B*.
10..	Calcite[a]	Calcite[a]	Calcite[a]	Calcite.[a]
9...	Schneebergite Chalcopyrite Magnetite	Schneebergite Chalcopyrite Magnetite	Schneebergite Chalcopyrite Magnetite	Schneebergite. Chalcopyrite. Magnetite.
8...	Chalcopyrite Magnetite	Chalcopyrite Magnetite	Chalcopyrite Magnetite	Chalcopyrite. Magnetite.
7...	White calcite		White calcite	White calcite.
6...	Magnetite		Black calcite and magnetite.	Black calcite and magnetite.
5...	Garnet	Garnet Chalcopyrite Breunnerite	Garnet	Garnet?
4...	Quartz Sphalerite	Quartz	Breunnerite	Quartz. Breunnerite.
3...		(?)		Magnetite.
2...		(?)		Sphalerite. Galena. Magnetite. Breunnerite.
1...	Sphalerite	(?)	Quartz	Sphalerite.

[a] Now removed.

This succession shows a marked uniformity. The first mineral of the specimens was either quartz or sphalerite. After this came bands composed of more than one mineral, such as sphalerite, quartz, magnetite, and breunnerite. Garnet occurs on all the specimens, either with or directly above the breunnerite, but always directly associated with it. The garnet is the only mineral which occurs not as distinct bands but as nodular masses, and it is found only in the breunnerite bands, from which it is probably derived, as stated both by Elterlein and by Eakle and Muthmann. All these writers, however, considered the garnet to be true schneebergite. Above the garnet comes a mixture of black calcite and magnetite, over which is a small band of purer white calcite. This white calcite grades into the mixture of chalcopyrite and magnetite which is the matrix of the schneebergite.

That the succession of minerals is not the reverse of that given is proved by their mode of occurrence as concentric fillings, in which, as shown in figure 78, the schneebergite is the nucleus. The mode of occurrence, as described by Elterlein, shows that they could not be concretions, growing from the center outward.

The association of schneebergite is characteristic. It lies on and embedded in the mixture of chalcopyrite and magnetite, which is surrounded by bands of minerals in a well-defined succession. The garnet, mistaken for schneebergite, has a different place in the order of succession.

There is also a gradual change in the state of oxidation of those elements existing in more than one form. The mineral first formed—sphalerite—has all its iron in the ferrous condition. The breunnerite likewise contains only ferrous iron. The next iron minerals to form, garnet and magnetite, have both ferrous and ferric iron, and in harmony with this partial oxidation to a higher valency, the mineral last formed, schneebergite, has its antimony in two states of oxidation.

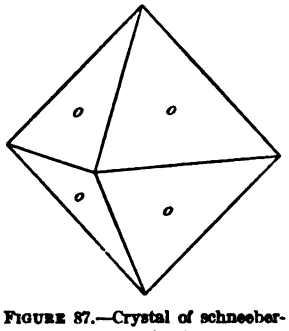


FIGURE 87.—Crystal of schneebergite, o{111}.

CRYSTALLOGRAPHY.

The crystals of schneebergite show only the octahedron $o\{111\}$ and have the appearance shown in figure 87. The measurements of Brezina, as given on page 82, show a very close agreement with the octahedral angle of the isometric system.

Nearly all the faces of the crystals measured were uneven and gave several indistinct reflections. The best measurement gave $o : o' =$ 109° 24′ (calculated, 109° 28′). By placing a crystal in polar position on the two-circle goniometer, it was seen that the reflections

from the four octahedral faces fell in a vertical line which had the correct ρ position for the isometric octahedron. Schneebergite is therefore, without question, isometric in its geometric symmetry.

PHYSICAL PROPERTIES.

Brezina gives a doubtful cleavage after {110}. No such cleavage could be detected by the writer, but a distinct cleavage parallel to the octahedron $o\{111\}$ was found. The cleavage is by no means as good as that of romeite from Brazil (the so-called atopite).

The density was given by Brezina as 4.1 (determined on 0.17 gram). The material used by him was without question not pure, and the amount of material used very small. A new determination of the density was made with a pycnometer on 2.0676 grams of pure material and found to be 5.41.

OPTICAL PROPERTIES.

The color of a mass of pure crystals is "honey-yellow" according to Ridgway's Color standards,[1] and the color of the powdered crystals is "baryte-yellow." The luster is adamantine. When examined optically, the crystals seem to be free from inclusions, and the suggestion arises that the magnetite inclusions observed by Brezina occurred not in the schneebergite but in the garnet, where such inclusions were also found by Eakle and Muthmann.

Schneebergite, being isometric, should be isotropic, but many of the crystals show anomalous low double refraction. The compound is probably dimorphous, the high temperature form being isometric.

The refractive index was determined by the embedding method by Mr. E. S. Larsen and found to be 2.09.

CHEMICAL PROPERTIES.

PYROGNOSTICS.

Schneebergite would be classed as infusible, but in fine splinters the edges are with difficulty fused and rounded. In closed and open tubes no reactions occur. The mineral is insoluble in acids, but it is decomposed without difficulty in a sodium carbonate fusion. It becomes readily reduced when heated in hydrogen.

HOMOGENEITY OF SAMPLE ANALYZED.

The microscopic examination did not reveal any inclusions of foreign matter in the crystals of schneebergite. Pieces of the specimens were crushed so as to separate the individual minerals, and by a long-continued process of hand picking, by the use of the electromagnet and of heavy solutions, and by treatment with acids, a pure sample was finally obtained. The acids used were hydrochloric, aqua

[1] Ridgway, Robert, op. cit., p. 32.

regia, and hydrofluoric. The concentration of the acids used was not great nor was their use long continued at any one time. It was found that schneebergite was slightly attacked by aqua regia, but as all the products of attack went into solution no differential separation of the constituents took place and moreover the total amount of material dissolved was very slight. The crushed material was finally subjected to another careful examination under a magnifying glass, and the few impurities which remained were picked out by hand.

The purification of the material, although not worked on continuously, extended over several months. A final sample of 2.0676 grams was obtained, in which no impurities could be detected by a microscopic examination.

ANALYTICAL METHODS USED.

The density of the sample was first determined with a pycnometer. The mineral was then air dried for several weeks and finally was ground in a mechanical grinder for several hours, as it was thought necessary to have the mineral in a state of very fine subdivision in order to obtain decomposition. The results of the analyses have indicated that for schneebergite and also for romeite (including the the Brazilian "atopite") a very fine powder is not necessary and that the difficulty of decomposition of these minerals has been exaggerated.

Part of the sample was fused in a platinum crucible with sodium carbonate, and in the resulting acid solution antimony was thrown out by hydrogen sulphide. In the filtrate iron and calcium were determined as usual. A special search was made for the elements reported by earlier investigators, and the following elements could not be detected in the sample: Copper, lead, bismuth, tin, arsenic, aluminum, zinc, magnesium, and potassium. These elements, as found by earlier analysts, doubtless owed their presence to admixed minerals. Another portion of the sample was reduced in hydrogen and the water formed was collected and weighed. The 0.5-gram samples were placed in a nickel boat, inserted in a hard-glass tube properly arranged, and a current of dried carbon dioxide was passed through the apparatus for an hour. The glass tube with its boat containing the finely powdered schneebergite was then dried by being gently heated, the current of carbon dioxide being continued. After cooling, hydrogen was passed through the apparatus for half an hour, after which, the weighed calcium chloride tube being attached, the mineral was gently heated until decomposition began. Toward the end of the operation the boat and its contents were heated to a dull red. The hydrogen used was generated by the action of sulphuric acid on zinc. The gas, first washed, was then passed

through an alkali solution of pyrogallic acid, then through sulphuric acid, and then through a tower of calcium chloride. Both gases passed through a different final series of three calcium chloride tubes placed just before the ignition tube containing the mineral. The percentage of water occurring as such in the mineral powder was determined by loss on ignition, as it did not belong to the mineral, but was introduced or absorbed by the very fine powder during the grinding of the sample. Individual unground crystals did not yield any water when ignited, as special tests on this point were made.

QUANTITATIVE COMPOSITION.

The results of the analysis are stated below. The antimony is reported as the metal (calculated from the weighed Sb_2S_3), and the oxygen combined with the antimony (calculated from the weighed H_2O) is given as such.

Analysis and ratios of schneebergite.

	Analysis.	Ratio.		
Sb	57.40	0.478		1.02 or 1
O	15.19	.948		2.03 or 2
FeO	8.51	.118	0.441	.94 or 1
CaO	17.42	.322		
Na_2O	.10	.001		
Insoluble [a]	.30			
H_2O [b]	1.67			
	100.59			

[a] A small residue of undissolved larger grains from the sodium carbonate fusion.
[b] Determined by loss on ignition. The water was absorbed by the finely ground powder, as special tests showed that the unground crystals yielded no water on ignition.

The amount of oxygen as actually determined by collecting the water given off on decomposing the mineral in hydrogen is 17.83 per cent. The amount of oxygen combined with the iron, or 1.90 per cent, is to be deducted from the 17.83 per cent, leaving 15.93 per cent of oxygen combined with the antimony. At the time this determination was made it was not known that the powdered substance had absorbed water during grinding. The tube containing the powdered schneebergite was heated before the quantitative determination was made, but it is not known whether the heat was sufficient to drive off all the absorbed water in the schneebergite powder. On the assumption that all the water was driven off, the figure above given for oxygen combined with antimony, namely, 15.93 per cent, is correct. If, however, none of the absorbed water was driven off, then the percentage of oxygen obtained is to be lowered by the amount of oxygen in the absorbed water, namely, 1.48 per cent, giving for

oxygen combined with antimony 14.45 per cent. As it is not known which condition is the true one, and as it is believed that an intermediate condition is probably more correct—that is, that some of the water was driven off and some retained—an average of the two figures, or 15.19 per cent, is taken as the true value.

The ratios of the analysis show that the oxidation of the antimony must be that expressed by the oxide Sb_2O_4. That such a result is obtained by either one of the three interpretations just given for the percentage of oxygen in the mineral is shown by the following calculation. With the determination of antimony (57.40 per cent Sb) as a basis, the required percentage of oxygen for the three possible states of oxidation of the antimony has been calculated. As can readily be seen, the determinations of oxygen agree only with the value calculated from the Sb_2O_4 state of oxidation.

Comparison of oxygen percentages in schneebergite.

	Per cent of oxygen.	
	Calculated.	Found.
Sb_2O_3	11.48	
Sb_2O_4	15.31	15.93 maximum. 15.19 average. 14.45 minimum.
Sb_2O_5	19.14	

The ratios yield the formula $SbO_2(R''O)$ or $R''SbO_3$, in which R″ is one-fourth Fe″ and three-fourths Ca. The formula may then be written more exactly $Fe''Ca_3Sb_4O_{12}$. The analyses of romeite, however, have shown that in these minerals the bases Ca, Fe″, Mn″, and Na_2 must be considered as isomorphously replacing one another, and the formula for schneebergite is therefore written in its simplest form as $CaSbO_3$. The antimony exists in two states of oxidation and the formula $4CaO.2Sb_2O_4(=4CaSbO_3)$ is interpreted as $2CaO.Sb_2O_3+2CaO.Sb_2O_5$.

Schneebergite, empirically $CaSbO_3$, is most simply regarded as a mixed salt, namely a calcium pyro-antimonite, $2CaO.Sb_2O_3$, with a calcium pyro-antimonate, $2CaO.Sb_2O_5$. To regard the trivalent antimony as a base, to be added on to the calcium, throws too heavy a burden on the pentavalent antimony, which must then serve as acid for an overwhelming base.

ROMEITE.

ORIGIN OF INVESTIGATION.

In order to compare the composition of schneebergite with that of romeite and atopite, it was necessary to undertake a reexamination, with analysis, of these two later minerals. Through correspondence a collection of romeite specimens was obtained from Capt. Albert Pelloux, of Genoa, which furnished the material for this description. The writer's thanks are due to Capt. Pelloux for his liberality in furnishing these rare and valuable specimens.

Atopite from the original locality at Långban, Sweden, described by Nordenskiöld, was not available, but as Hussak had stated that the results of his study of the later-described Brazilian material agreed with the description and composition of the original Swedish atopite, specimens of the Brazilian atopite were purchased from Groebel & Wendler, of Geneva, Switzerland, and form the basis of the writer's work on the mineral. Unexpectedly, the analysis of the Brazilian atopite showed that mineral to have the same composition as the Italian romeite, and a critical review of Hussak's data showed that his statement that the Brazilian mineral agrees completely with the original atopite is incorrect.

HISTORICAL SKETCH.

Romeite was described by Damour [1] in 1841, and as the result of a later analysis, published in 1853, the composition of the mineral has been given in all textbooks as $CaSb_2O_4$. Moreover, as a result of Dufrénoy's contribution to Damour's first article, the mineral has always been considered as tetragonal, with angles very close to the isometric octahedron. The tetragonal character of the mineral was considered verified by Bertrand's observation of strong double refraction and uniaxial interference figure. Bertrand considered the tetragonal octahedron as built up of a group of eight 90° rhombohedra grouped around a point.

The measurements of Dufrénoy, published in 1841 and made by means of the sun's reflection, are not confirmed by the recent work of Pelloux, whose measurements agree closely with those required for isometric symmetry. Pelloux measured (111): (110) as 35°13′ (for isometric system this angle is 35° 16′); and (311): (131) as 50° 20′ (for isometric system this angle is 50° 28½′). He remarks, moreover,

[1] See p. 96 for bibliography.

that the octahedron is too uneven to yield good measurements, a statement also made by Dufrénoy and confirmed by the writer. Pelloux has determined the forms $d\{110\}$, $m\{311\}$, and $n\{211\}$, in addition to the octahedron $o\{111\}$.

Nordenskiöld, in 1877, described a new mineral from Långban, Sweden, which he named atopite, and showed wherein, if Damour's results were correct, atopite differed considerably in chemical composition from the older known mineral.

The paper by Hussak, describing the Brazilian so-called atopite, is the last published contribution dealing with the chemical composition of the mineral. Hussak claimed that his analysis agreed with that of the Swedish atopite and fully verified the formula $2CaO.Sb_2O_5$, but, as is shown later in this paper, his analysis leads not to the atopite formula just given but to the formula of romeite, $5CaO.3Sb_2O_5$. The Brazilian so-called atopite is in fact identical with the romeite from Italy.

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PARAGENESIS.

A simple inspection of the specimens received from Capt. Pelloux showed that the Italian romeite occurs in minute veins traversing the associated minerals or more abundantly lying along the boundary of masses of two different minerals. A characteristic association seems to be that figured in Plate IV, *A* (p. 89), where minute veins of romeite lie between the braunite and the aggregate of albite and piedmontite. The mineral is also found as nests and veins in the associated braunite, albite, piedmontite, etc. The nests seem to be local enlargements of the veins rather than distinct isolated bodies—at least, the specimens at the writer's disposal all show the romeite in distinct veins. The occurrence of romeite as the main constituent of a vein seems therefore to be somewhat different from that of schneebergite, which is not known to occur as veins but only as the filling of ellipsoidal cavities.

The romeite from Brazil (the so-called atopite) occurs in cavities and also as isolated crystals scattered through the secondary manganese oxides of the Miguel Burnier manganese district. The specimens obtained from Groebel & Wendler show the romeite as isolated crystals or groups of crystals embedded in the compact manganese oxide, which is associated with quartz on some of the specimens. The occurrence of the well-formed isolated crystals of romeite in the massive compact manganese ore recalls the occurrence of well-formed pyrite crystals in compact schists and shales and suggests a similar origin.

CRYSTALLOGRAPHY.

The crystals of the Italian romeite at the writer's disposal are not suitable for accurate measurement. The octahedron is the only form identified, but its surfaces are all uneven and give a group of reflections on the goniometer. It could be shown, however, on the two-circle goniometer that the angles of the octahedron of romeite are very close to those of the isometric octahedron.

The crystals of romeite from Brazil, on the other hand, show even and brilliant faces which yielded perfect reflections. Although Hussak does not give any measured angles, he states that the mineral is isometric and holohedral and shows predominantly the octahedron $o\{111\}$, with $d\{110\}$, $a\{100\}$, and more rarely $m\{311\}$. Pelloux gives o d m with $n\{211\}$ for the Italian romeite.

On the Brazilian romeite the ρ angle of the octahedron was measured as follows:

Measurements of the ρ angle of the octahedron $o\{111\}$ on romeite from Brazil.

[Calculated ρ=54°44′.]

1				2	
°	′	°	′	°	′
54	41	54	44	54	42
54	43	54	44	54	44
54	47	54	45	54	44
54	44	54	45	54	46

The angle o to o' was also measured directly as 109° 27′ (calculated 109° 28′). The isometric symmetry of the romeite from Brazil is therefore established, and the isometric form of the mineral from Italy, as indicated by Pelloux's measurements, is confirmed.

The form $v\{133\}$, found by Schröder on the Brazilian romeite, was also observed once as a line face by the writer.

Measured ϕ, 45° 00′; calculated ϕ, 45° 00′. Measured ρ, 76° 11′; calculated ρ, 76° 44′.

PHYSICAL PROPERTIES.

An imperfect octahedral cleavage was noted on the crystals from Italy, whereas the Brazilian romeite showed a good octahedral cleavage.

The density was determined by Damour for small crystalline grains as 4.714 and 4.711 and for very fine powder as 4.675. The value given in textbooks, namely, 4.713, is the average of the first two of Damour's determinations. In his analysis, made presumably on material similar to that used for his determinations of density, Damour gives 2.86 per cent of soluble silica and foreign siliceous material (quartz, albite?). If an arbitrary density of 2.7 is assigned to the 2.86 per cent of foreign matter in his sample of romeite, and the density (4.713) is corrected, a new value of 4.77 (Damour) is obtained for the pure romeite. The even higher value 5.074 was obtained by the writer by determining the density of 2.6768 grams of pure romeite from Italy with the pycnometer. The density of the Brazilian romeite (given by Hussak as 5.1) was determined by the writer on 6.7372 grams to be 5.044.

OPTICAL PROPERTIES.

The color of uncrushed romeite from Italy, freed from the interfering effect of the strongly colored associated minerals, is a "russet" according to Ridgway's "Color standards." The color of powdered romeite is a "seashell-pink." The color of the Brazilian romeite is "old gold," and the color of its powder is "very light buff." The luster is vitreous to greasy and not as adamantine as that of schneebergite.

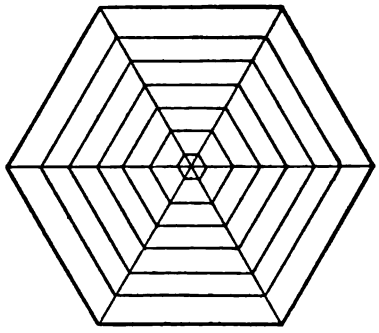

FIGURE 88.—Optical structure of crystal of romeite.

Optically the mineral is doubly refracting, although the material examined shows low double refraction and not high double refraction, as found by Bertrand and by Pelloux. The interference colors are seldom above a yellow of the first order. The structure of the Brazilian romeite as revealed between crossed nicols is shown in figure 88. The mineral, like schneebergite, is probably dimorphous, the high-temperature form being isometric.

The refractive index was determined by Mr. E. S. Larsen as 1.87 on romeite from Italy and 1.83 on romeite from Brazil. The Brazilian romeite varied somewhat in its index of refraction and birefringence.

CHEMICAL PROPERTIES.

PYROGNOSTICS.

When heated before the blowpipe, romeite is infusible. In the closed and open tubes no reactions take place. The mineral is insoluble in acids, although readily decomposed by fusion with sodium carbonate.

QUANTITATIVE COMPOSITION.

Pure samples were obtained by the same procedure as was used for schneebergite. The methods of analysis were also the same. The results of the quantitative analysis of romeite from Italy are as follows:

Analysis and ratios of romeite from Italy.

	Analysis.	Ratios.		
Sb	56.15	0.467		5.99 or 6×1.00
O	18.57	1.161		14.88 or 15×0.99
FeO	1.12	.016	.399	5.12 or 5×1.02
MnO	6.27	.088		
CaO	15.81	.282		
Na_2O	.81	.013		
H_2O	1.39			
	100.12			

The ratios yield the formula $5R''O.Sb_6O_{15}$, in which R″ is composed chiefly of Ca but contains also smaller amounts of Fe″, Mn″, and Na_2. The formula may be written, considering all of the R″ as Ca, as $5CaO.3Sb_2O_5$ or $Ca_5Sb_6O_{20}$.

Romeite can not be directly interpreted as a salt of any of the six acids given on page 104, if all the antimony is considered as an acid. The mineral can be regarded as a salt of a partly dehydrated pyro-antimonic acid, $3Sb_2O_5.6H_2O - H_2O = 3Sb_2O_5.5H_2O$ or $H_{10}Sb_6O_{20}$. Another interpretation would be to consider it a salt of a mixed acid, two parts of pyro-antimonic acid with one of meta-antimonic acid, $2(Sb_2O_5.2H_2O) + (Sb_2O_5.H_2O) = H_6Sb_4O_{14} + H_2Sb_2O_6$. It is preferred to regard romeite as a pyro-antimonate.

The interpretation of the percentage of oxygen in the mineral, as determined by reduction in hydrogen, is affected in a similar way to that of schneebergite (p. 93), on account of the small amount of water absorbed by the fine powder during grinding. The results are treated in the same way as was done for schneebergite, and the figures obtained are as follows:

Comparison of oxygen percentages of romeite from Italy.

	Per cent of oxygen.	
	Calculated.	Found.
Sb_2O_3	11.21	
Sb_2O_4	14.95	
Sb_2O_5	18.69	17.95 minimum. 18.57 average. 19.18 maximum.

The above results show that the amount of oxygen combined with the antimony is such that the state of oxidation of the metal is that expressed by the formula Sb_2O_5.

The analysis of romeite from Brazil gave the following results:

Analysis and ratios of romeite from Brazil.

	Analysis.	Ratios.		
Sb	56.02	0.466		5.95 or 6×0.99
O	18.70	1.169		14.93 or 15×1.00
FeO	1.29	.018	0.401	5.12 or 5×1.02
MnO	2.62	.037		
CaO	14.81	.264		
Na_2O	5.08	.082		
H_2O	1.12			
	99.64			

The ratios yield the same formula as was obtained from the analysis of the Italian romeite, namely, $Ca_5Sb_6O_{20}$. The ratio of Na_2O to $CaO+FeO+MnO$ is 1 : 3.89, or nearly 1 : 4, so that the formula could be written $NaCa_4Sb_6O_{20}$. To judge from the analyses, however, it seems necessary to regard the Na_2O, FeO, and MnO as replacing the CaO and to group them together under CaO

Interpretation of the percentage of oxygen found yields the following results for the Brazilian romeite:

Comparison of oxygen percentages of romeite from Brazil.

	Per cent of oxygen.	
	Calculated.	Found.
Sb_2O_3	11.18	
Sb_2O_4	14.92	
b_2O_5	18.64	18.20 minimum. 18.70 19.19 maximum.

The results show that, in complete conformity with the analysis of the Italian romeite, the antimony in the Brazilian mineral is in its highest state of oxidation, namely, Sb_2O_5.

Hussak stated that the formula of atopite (from Sweden), namely, $2(Ca, Mn, Na_2).Sb_2O_7$ or $2R''O.Sb_2O_5$, also accorded with his analysis of the Brazilian mineral. That such assumed accordance does not exist can be readily shown.

The analysis of the Swedish atopite, as given by Nordenskiöld, is as follows:

Analysis and ratios of atopite from Sweden.

[A. E. Nordenskiöld, analyst.]

	Analysis.	Ratios.		
Sb_2O_5	72.61	0.227		1.00
FeO	2.79	.039		
MnO	1.53	.022		
CaO	17.85	.319	0.460	2.03
K_2O	.86	.009		
Na_2O	4.40	.071		
	100.04			

The ratios yield the simple formula $2\ R''O.Sb_2O_5$, in which $R = Fe''$, Mn'', Ca, K_2, and Na_2. Another analysis would definitely determine whether this simple formula is correct or whether, as a possibility, the Swedish atopite is not the same as romeite. There seems to be no reason, however, for questioning Nordenskiöld's analysis, but his figures are very similar to those obtained for romeite.

The analysis of the mineral from Brazil, by Hussak, gave the following results:

Analysis and ratios of romeite (wrongly called atopite) from Brazil.

[E. Hussak, analyst.]

	Analysis.	Ratios.		
Sb_2O_5	76.20	0.238		2.99 or 3
FeO	Trace.			
MnO	5.70	.080		
CaO	12.68	.226	0.398	5.01 or 5
Na_2O	5.70	.092		
K_2O	Trace.			
	100.28			

The ratios yield the formula $5R''O.3Sb_2O_5$, which is identical with that obtained from the writer's analysis of romeite from Brazil and from Italy. If the ratio of Sb_2O_5 is made 1.00, then the ratio for

R″O becomes 1.67 and not 2, as would be required if Hussak's analysis led to the same result as Nordenskiöld's analysis. The mineral from Brazil is therefore not atopite but romeite, as proved by the independent analyses made by Hussak and by the writer. The three analyses of romeite given above are shown together in the following table, to which is also added Damour's last analysis:

Analyses of romeite.

	Italy.		Brazil.	
	Damour.	Schaller.	Hussak.	Schaller.
Sb_2O_5	[a] 77.61	74.72	76.20	74.72
FeO	1.70	1.12	Trace.	1.29
MnO	1.21	6.27	5.70	2.62
CaO	16.29	15.81	12.68	14.81
Na_2O	.....	.81	5.70	5.08
K_2O	.....	.....	Trace.	.....
H_2O	.....	1.39	.....	1.12
SiO_2, etc	2.86	.....	.....	.....
	99.67	100.12	100.28	99.64

[a] This represents the percentage of what Damour considered $Sb_2O_3+Sb_2O_5$.

The last three analyses all yield the same formula, namely, $5CaO.3Sb_2O_5$. The results of Damour's analysis must be considered inaccurate so far as the determinations of the antimony and of the oxygen combined with it are concerned. The analyses show, moreover, the variability in the replacement of CaO by the other bases and the improbability that one of these bases (soda, for example) should be considered by itself.

The last analysis of romeite made by Damour (in his two earlier analyses he did not determine the state of oxidation of the antimony) is reproduced below with the ratios derived therefrom.

Analysis and ratios of romeite from Italy.

[A. Damour, analyst.]

	Analysis.	Ratios.		
Sb	62.18	0.517		3.13 or 3×1.04
O	15.43	.964		5.84 or 6×0.97
FeO	1.70	.024	0.332	2.01 or 2×1.01
MnO	1.21	.017		
CaO	16.29	.291		
SiO_2, etc	2.86			
	99.67			

The ratios obtained give the formula $Ca_2Sb_3O_8$ or $4CaO.3Sb_2O_4$, which, as stated by Dana,[1] agrees closer with the analysis than the simpler formula $CaSb_2O_4$ usually given in textbooks.

Nordenskiöld failed to get decisive results on atopite by reducing the mineral at a low temperature in hydrogen and determining the state of oxidation of the antimony by the loss in weight of the mineral, as was done by Damour, and ascribes his failure to three conditions—the volatility of some of the antimony, even at a low temperature; the incompleteness of the reduction even after long-continued heating in hydrogen; and the fact that a part of the unreduced mineral seemed to be soluble, after the treatment in hydrogen, in hydrochloric acid, whereas the untreated material is not soluble in acids.

Whatever may be the reason to which the difficulty is assigned, Damour's results were not verified by the writer's analysis, and as his figures yield the rather improbable formula $4CaO.3Sb_2O_4$, it must be concluded that his figures do not accurately represent the composition of the Italian romeite.

[1] Dana, E. S., System of mineralogy, 6th ed., p. 862, 1892.

THE NATURAL ANTIMONITES AND ANTIMONATES.

The acids of antimony are six in number, as follows:

Acids of antimony.

Name of acid.	Name of salt.	Formula.
Ortho-antimonous	Ortho-antimonite	$Sb_2O_3.3H_2O=H_6Sb_2O_6$.
Pyro-antimonous	Pyro-antimonite	$Sb_2O_3.2H_2O=H_4Sb_2O_5$.
Meta-antimonous	Meta-antimonite	$Sb_2O_3.H_2O=H_2Sb_2O_4$.
Ortho-antimonic	Ortho-antimonate	$Sb_2O_5.3H_2O=H_6Sb_2O_8$.
Pyro-antimonic	Pyro-antimonate	$Sb_2O_5.2H_2O=H_4Sb_2O_7$.
Meta-antimonic	Meta-antimonate	$Sb_2O_5.H_2O=H_2Sb_2O_6$.

Hypo-antimonic acid, $H_2Sb_2O_6$, is supposedly derived from antimony tetroxide, Sb_2O_4, but this tetroxide may be just as well considered a salt, namely, antimonous ortho-antimonate, $Sb_2''' (Sb'''''O_4)_2$.

The natural antimonites and antimonates are grouped according to the acid in the following tabulation. In addition to the antimonites and antimonates, shown in heavy type, the list includes some examples of corresponding arsenates, phosphates, vanadates, columbates, tantalates, nitrates, and titanates.

Ortho-antimonites, salts of ortho-antimonous acid, $H_6Sb_2O_6$:

No minerals known.

Pyro-antimonites, salts of pyro-antimonous acid, $H_4Sb_2O_5$:

No minerals known. Schneebergite may be a salt of a mixed acid corresponding to $H_4Sb_2O_5+H_4Sb_2O_7$.

Meta-antimonites, salts of meta-antimonous acid, $H_2Sb_2O_4$:

Nadorite.....$(PbCl)'_2Sb_2O_4$.

Schneebergite may be a salt of a mixed acid corresponding to $H_2Sb_2O_4+H_6Sb_2O_8$.

Ortho-antimonates, salts of ortho-antimonic acid, $H_6Sb_2O_8$:

Monimolite.....$(Pb,Fe,Ca)''_3Sb_2O_8$.....Isometric.
Berzeliite.....$(Ca,Mg,Mn)''_3As_2O_8$.....Isometric.
Pseudoberzeliite.....$(Ca,Mg,Mn)''_3As_2O_8$.....Orthorhombic (?).
Caryinite.....$(Pb,Mn,Ca,Mg)''_3As_2O_8$.....Monoclinic (?).
Fergusonite.....$Y'''_2Cb_2O_8$.....Tetragonal.
Pucherite.....$Bi'''_2V_2O_8$.....Orthorhombic.
Triphylite.....$(LiFe'')'''_2P_2O_8$.....Orthorhombic.
Wagnerite.....$(MgF)'_2Mg_2P_2O_8$.....Monoclinic.
Amblygonite.....$(AlF)''_2Li_2P_2O_8$.....Triclinic.
Cervantite.....$Sb'''_2Sb'''''_2O_8$.....Orthorhombic.
Stibiconite.....$Sb'''_2Sb'''''_2O_8.2H_2O$.....Amorphous.
Flajolotite.....$Fe'''_2Sb'''''_2O_8.xH_2O$.....Amorphous.

Schneebergite may be a salt of a mixed acid corresponding to $H_6Sb_2O_8+H_2Sb_2O_4$.

Pyro-antimonates, salts of pyro-antimonic acid, $H_4Sb_2O_7$:

Atopite	$Ca_2Sb_2O_7$	Isometric.
Microlite [1]	$Ca_2Ta_2O_7$	Isometric.
Tripuhyite	$Fe''_2Sb_2O_7$	Biaxial.
Bindheimite	$Pb_2Sb_2O_7.xH_2O$?	Amorphous.
Romeite	$Ca_5Sb_6O_{20}$	Isometric.

Schneebergite may be a salt of a mixed acid corresponding to $H_4Sb_2O_7+H_4Sb_2O_5$.

Meta-antimonates, salts of meta-antimonic acid, $H_2Sb_2O_6$:

Stibianite [2]	$H_2Sb_2O_6$(?).	
Lewisite	$3(CaSb_2O_6)$ $2(CaTiO_3)$	Isometric.
Mauzeliite	$(CaSb_2O_6)$ $((CaF)_2TiO_3)$ (?)	Isometric.
Perovskite	$CaTiO_3$	Isometric.
Pyrochlore	$(CaTiO_3.n(CaCb_2O_6)$ (?)	Isometric.
Derbylite	$(Fe''Sb_2O_6)$ $5(Fe''TiO_3)$	(?)Orthorhombic.
Columbite	$Fe''Cb_2O_6$	Orthorhombic.
Niter	$K_2N_2O_6$	Orthorhombic.

Lewisite (with which mauzeliite is identical) seems to be predominantly $CaSb_2O_6$ with a small amount of perovskite isomorphously mixed with it.

Derbylite seems to represent an orthorhombic modification of ($Fe''TiO_3$), already known in a tetragonal form (in iserite), a trigonal form (ilmenite), and possibly in an isometric form (in pyrochlore, dysanalyte, or knopite?).

Mixed antimony acids:

Schneebergite	$2CaO.Sb_2O_3$ $2CaO.Sb_2O_5$	Isometric.

Romeite may be a salt of a mixed acid corresponding to $2(H_2Sb_2O_6)+H_6Sb_2O_8$.

Schneebergite may be a salt of a mixed acid corresponding to $H_2Sb_2O_6+H_6Sb_2O_6$.

Relations not clear:

Ochrolite	$Pb_6Cl_4Sb_2O_7$	Orthorhombic.

The relations of ochrolite and ecdemite ($Pb_6Cl_4As_2O_7$) are not clear.

Manganostibiite	$9MnO.Sb_2O_5$?	Orthorhombic (?).

The other antimonates of Igelström are too indefinite for consideration.

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[1] Apparently essentially $Ca_2Ta_2O_7$. Sodium, fluorine, and other elements seem to be present in some varieties of microlite.

[2] According to the formula given stibianite would not be an antimonate but the antimonic acid itself. The composition of stibianite can not be considered as conclusively determined.

VELARDEÑITE, A NEW MEMBER OF THE MELILITE GROUP.

The compound $2CaO.Al_2O_3.SiO_2$ has been found to play an important part as one of the members of an isomorphous series of minerals whose mixtures are well known under the names of melilite and gehlenite. The relations of the members of the melilite group are given in the following paper. A review of the literature on the composition of melilite and gehlenite has shown that the "gehlenite" from the Velardeña mining district, in Mexico, described by Wright[1] in 1908, is in fact the compound $2CaO.Al_2O_3.SiO_2$, mixed with about 20 per cent of åkermanite. This compound also occurs in quantity in several melilites and gehlenites. It therefore deserves to be recognized as a mineral species, which is appropriately named velardeñite, after the locality.

Velardeñite was artificially prepared by Weyberg[2] in 1904 by fusing kaolin with a small amount of calcium bromide. The material, after the soluble portion of the melt had been dissolved, consisted of minute square prisms, which gave parallel extinction and in cross section were uniaxial, negative. The prisms were therefore a combination of a tetragonal prism with the basal pinacoid. Two analyses of material, not entirely pure, were made by Weyberg and, together with the calculated percentages of the formula $2CaO.Al_2O_3.SiO_2$, are reproduced in the table below.

Analyses of artificial velardeñite.

[Z. Weyberg, analyst.]

	1	2	Calculated.
SiO_2	25.79	22.56	21.99
Al_2O_3	36.66	37.06	37.23
CaO	37.42	40.30	40.78
	99.87	99.92	100.00

Some years later the same compound was artificially prepared by Shepherd and Rankin,[3] who also give the chief properties of the material. (The optical determinations were made by F. E. Wright.)

[1] Wright, F. E., On three contact minerals from Velardeña, Durango, Mexico [gehlenite, spurite, and hillebrandite]: Am. Jour. Sci., 4th ser., vol. 26, p. 545, 1908.

[2] Weyberg, Z., Ueber einige basische haloidhaltige Calciumalumosilicate: Centralbl. Mineralogie, 1904, pp. 729–734.

[3] Shepherd, E. S., and Rankin, G. A., Preliminary report on the ternary system $CaO-Al_2O_3-SiO_2$; a study of the constitution of Portland cement clinker: Jour. Ind. and Eng. Chemistry, vol. 3, p. 211, 1911.

The following table shows a comparison between the properties of velardeñite from Mexico, as given by Wright, and the properties of artificial pure velardeñite:

Properties of velardeñite.

	Velardeñite from Mexico (80 per cent pure velardeñite, 20 per cent pure åkermanite).	Artificial pure velardeñite.
Symmetry	Tetragonal	Tetragonal.
Cleavage	{001} imperfect,[a] (prism) poor	{001} distinct.
Density	3.039	3.038.
Sign	Negative	Negative.
ω	1.666	1.667.
ϵ	1.661	1.658.
$\omega-\epsilon$	0.0055	0.009.

[a] Well marked in thin section.

The other properties of velardeñite, as given by Wright, are as follows: Color, dark gray or gray-black from minute inclusions of magnetite and other particles, rarely amber-yellow; luster, resinous to greasy; translucent to transparent in thin flakes; fracture, uneven and irregular, conchoidal to splintery; hardness about 5.5; gelatinizes readily with acid and fuses with difficulty.

The interpretation of Allen's analysis, as quoted by Wright, is shown in the table below. The analysis has been recalculated by combining TiO_2 with SiO_2, Fe_2O_3 with Al_2O_3, $FeO+MnO$ with MgO, and K_2O+Na_2O with CaO, neglecting the water (1.85 per cent), and reducing the analysis to 100 per cent. The formula of åkermanite is $4MgO.8CaO.9SiO_2$. (See p. 116.)

Comparison of velardeñite analyses.

	Original analysis by E. T. Allen.	Analysis recalculated.	Calculated composition, 79.8 per cent velardeñite, 20.2 per cent åkermanite.	Difference.
SiO_2	26.33	26.98	27.03	+0.05
Al_2O_3	27.82	29.53	29.68	+ .15
CaO	39.55	40.70	40.46	− .24
MgO	2.44	2.79	2.83	+ .04
TiO_2	.03			
Fe_2O_3	1.43			
FeO	.50			
MnO	.01			
Na_2O	.21			
K_2O	.10			
H_2O	1.85			
	100.27	100.00	100.00	

The interpretation of the analysis of the mineral from Velardeña shows a close agreement between the analytical figures and the figure calculated for the assumed mineral composition.

Of the seventeen analyses of members of the melilite series given in the following paper, six show no velardeñite and the remaining eleven show that it is present, in isomorphous mixture, to the following percentages: 6.5, 9.5, 9.8, 11.3, 15.0, 15.8, 43.5, 44.7, 55.6, 63.8, 79.3.

As three of the analyses show the compound $2CaO.Al_2O_3.SiO_2$ to be present in natural minerals in excess of 50 per cent, it is justifiable to consider it a definite mineral species, velardeñite, with the properties given.

THE MELILITE GROUP.

HISTORICAL SKETCH.

REVIEW OF OLD THEORIES.

The composition of the melilite group has never been satisfactorily explained. The earlier writers assigned definite formulas to melilite and to gehlenite, although these are, as Dana [1] says, "uncertain, since the analyses fail to agree." The analyses of gehlenite, as listed by Dana, agree better with a single definite formula than those grouped under melilite.

Vogt [2] suggested that the natural melilites were mixtures of gehlenite ($3CaO.Al_2O_3.2SiO_2$) and an artificial product of the general formula $4R''O.3SiO_2$, to which the name åkermanite [3] was given. Calcium was the predominant base of this compound, and the formula of åkermanite has been written $4CaO.3SiO_2$, with appreciable amounts of MgO and other bases replacing, in part, the CaO. The failure of Vogt's theory to find general acceptance is due to the facts that (1) he assumed gehlenite, $3CaO.Al_2O_3.2SiO_2$, as one of the end members, whereas gehlenite is not a distinct and definite species but is itself a variable mixture of definite end members; and (2) he assumed the formula $4CaO.3SiO_2$ for åkermanite, whereas the correct formula is $4MgO.8CaO.9SiO_2$.

Bodlaender [4] found that the analyses of natural melilites did not agree with Vogt's theory and suggested that the optically negative melilites were mixtures of $R''SiO_3$ with $R''R'''_2O_4$, whereas the optically positive melilites represented mixtures of $R''SiO_3$ with $R''_3R'''_2O_6$.

Zambonini [5] has adopted Bodlaender's theory, although in an earlier paper [6] he had considered three possible explanations of the composition of the melilite group. If gehlenite ($3CaO.Al_2O_3.2SiO_2$) is considered as one end member, then, according to Zambonini, the other end member is $CaSiO_3$ and melilites are mixtures of the two types of compounds $R''_3R'''_2Si_2O_{10}$ and $R''SiO_3$. On the other

[1] Dana, E. S., System of mineralogy, 6th ed., p. 475, 1892.

[2] Vogt, J. H. L., Mineralbildung in Schmelzmassen, p. 96, 1892.

[3] Åkermanite was named after R. Åkerman and, as originally given by Vogt, is spelled with only one n. The spelling åkermannite, sometimes seen, is erroneous. The å is pronounced like long o.

[4] Bodlaender, G., Die Zusammensetzung des Meliliths: Neues Jahrb., 1892, Bd. 1, p. 53; 1893, Bd. 1, p. 15.

[5] Zambonini, F., Mineralogia Vesuviana, p. 254, 1910.

[6] Zambonini, F., Über eine krystallizierte Schlacke der Seigerhütte bei Hettstedt, nebst Bemerkungen über die chemische Zusammensetzung des Melilith: Zeitschr. Kryst. Min., vol. 41, p. 226, 1906.

hand, he states that melilites may be treated as having the general composition $R''R'''_2Si_2O_8.nR''_2SiO_4$. Zambonini also states that Bodlaender's theory, according to which melilites are composed of $R''SiO_3$ and $R''Al_2O_4$, agrees well with the facts.

Busz and Rüsberg,[1] in a recent paper, gave analyses of two samples of artificial melilite crystals, and, having found that Vogt's theory does not fit their analyses, they suggested that melilite is a mixture of either (1) gehlenite and $R''_2Si_2O_7$, or (2) the three components $3RO''.R'''_2O_3.2SiO_2$ (gehlenite), Ca_2SiO_4, and $CaSiO_3$.

Clarke[2] has recently suggested that gehlenites are mixtures of $2CaO.Al_2O_3.SiO_2$ and $9CaO.Al_2O_3.6SiO_2$.

Several other theories have been proposed, but, as admitted by their originators, they are not entirely satisfactory for explaining all the observed facts and need not be repeated here.

It seems to the writer that, with the exception of Vogt's, all the proposed theories are mainly attempts to express the composition of a given melilite by the summation of a number of compounds whose only reason for existence is that they are rational and theoretically possible chemical compounds. They show no relationship either among themselves or to the melilites in form or in properties. What resemblance is there between melilite and $CaSiO_3$ or Ca_2SiO_4, or for that matter why should the metasilicate and orthosilicate of lime be grouped together in isomorphous mixture when the properties of their known forms are so different?

If it is admitted that melilite represents an isomorphous mixture of a certain number of end products, then the problem is solved when these end members are identified. But these end members must satisfy the requirements of isomorphism; they must be related chemically, they must have a similar crystal form, they must form mixtures with the same crystal forms as the end members themselves, and all natural occurrences of melilite must be capable of being expressed quantitatively as mixtures of these end members.

All the proposed theories fail to meet these requirements, although Vogt's theory comes nearest to the truth. The essence of his theory is correct, but the foundations are not correct—the composition of his end members was not correctly expressed.

CHARACTERISTICS OF THE MELILITE GROUP.

The melilite group is well defined and includes the minerals known under the names melilite, gehlenite, and fuggerite. They are tetragonal, and when in distinct crystals form short, square prisms and

[1] Busz, K., and Rusberg, F. W., Mineralogisch-chemische Untersuchungen am Olivin- und Melilithkristallen in Hochofenschlacken: Centralbl. Mineralogie, 1913, p. 625.

[2] Clarke, F. W., The constitution of the natural silicates: U. S. Geol. Survey Bull. 588, pp. 31–34, 1914.

tabular forms (especially the artificial products). The cleavage is parallel to the base and the prism. The hardness is from 5 to 6, the density 2.9 to 3.1, the refractive index between 1.60 and 1.67, and the double refraction low. Some crystals are positive and others negative. Chemically the minerals are silicates of lime and alumina with smaller and varying amounts of magnesia, alkalies (especially soda), iron, etc. They readily gelatinize with acids.

The properties of the minerals of the melilite group, as outlined above, are characteristic and also fairly uniform. It follows, therefore, that the properties of the end members are probably similar among themselves and similar to those given above for the members of the group. In fact, the properties of the mixtures, as given above for the melilites (and gehlenites), are so nearly constant that the properties of the end members may be almost determined from the properties of their mixtures. One of the end members must have a density of about 2.9, another of about 3.1; the refractive index of one must be about 1.60, of another 1.67; one must be negative, another positive. The properties of the end members as proposed herein are consistent with the properties of their mixtures (melilites, gehlenites).

NEW THEORY.

PRIMARY COMPOUNDS.

NATURAL ANHYDROUS CALCIUM-ALUMINUM SILICATES.

A review of the literature shows that the anhydrous calcium-aluminum silicates occurring in nature are few in number. They are given below, with their crystal symmetry.

Anhydrous calcium-aluminum silicates occurring in nature.

Name.	Formula.	Crystal symmetry.
Anorthite	$CaO.Al_2O_3.2SiO_2$	Triclinic.
Didymolite	$2CaO.3Al_2O_3.9SiO_2$	Monoclinic.
Grossularite	$3CaO.Al_2O_3.3SiO_2$	Isometric.
Sarcolite	$3CaO.Al_2O_3.3SiO_2$	Tetragonal.
Velardeñite	$2CaO.Al_2O_3.SiO_2$	Tetragonal.
Melilite	(?)	Tetragonal.
Gehlenite	(?)	Tetragonal.

Sphenoclase, considered a doubtful species with the formula $6CaO.Al_2O_3.6SiO_2$, has been shown by V. M. Goldschmidt[1] to be a rock composed chiefly of pyroxene and grossularite.

[1] Goldschmidt, V. M., Ueber den sogenannten Sphenoklas: Centralbl. Mineralogie, 1911, pp. 35–36.

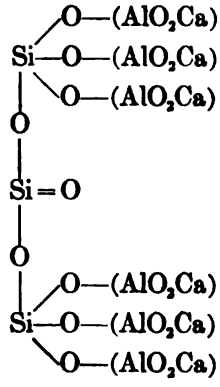
Meionite, supposed to be $4CaO.3Al_2O_3.6SiO_2$, has been shown by Borgström [1] to have the composition $CaCO_3.3CaAl_2Si_2O_8$.

To the above list of minerals is added åkermanite, a tetragonal silicate of lime and magnesia, which has the crystal form of melilite, and whose physical and optical properties are also very similar to those of melilite.

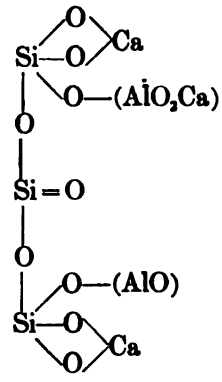
Sarcolite and velardeñite are the only tetragonal minerals listed above whose composition is definitely known. A few trials soon showed that all the suitably described members of the melilite and gehlenite group can be satisfactorily explained as isomorphous mixtures of the primary compounds, sarcolite ($3CaO.Al_2O_3.3SiO_2$), a theoretical soda-sarcolite ($3Na_2O.Al_2O_3.3SiO_2$), velardeñite ($2CaO.Al_2O_3.SiO_2$), and åkermanite ($4MgO.8CaO.9SiO_2$). Sarcolite and åkermanite occur in nature in a pure state as distinct mineral species, and velardeñite forms 80 per cent of a mineral occurring at Velardeña, Mexico, åkermanite forming the remaining 20 per cent. The physical and optical properties of these minerals are known and well defined and the important ones are grouped together on page 117.

The chemical composition of these tetragonal primary compounds, if expressed by empirical formulas, does not show a close relationship, but their formulas may be written in such a way as to suggest that a possibility of relationship exists, as shown by the formulas given below. No contention is made that these formulas structurally express the composition of the individual minerals; they are given only to show that a possible chemical relation exists between the minerals above named, which, in isomorphous mixture, comprise the minerals of the melilite group. Inasmuch as no aluminum is present in åkermanite, it is necessary to consider that the aluminum in sarcolite and velardeñite plays the part of a base and not an acid. In the formulas given below the univalent group (AlO_2Ca), or —Al Ca, is the only base in velardeñite. Two forms for sarcolite are given to show better the relationship of sarcolite to velardeñite and to åkermanite, respectively. The sarcolite 1 formula is more closely related to that of velardeñite than the sarcolite 2 formula, but in turn the formula of sarcolite 2 is more closely related to that of åkermanite than the formula of sarcolite 1.

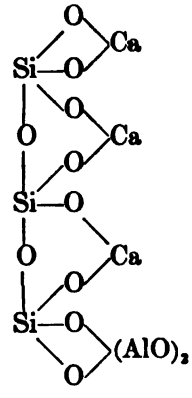
[1] Borgström, L. H., Zeitschr. Kryst. Min., vol. 54, p. 238, 1914.



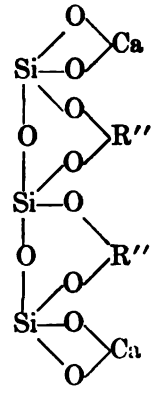
Velardefiite.



Sarcolite 1.



Sarcolite 2.



Åkermanite. R''=(Ca, Mg) in the ratio of 1:2.

SARCOLITE.

Sarcolite ($3CaO.Al_2O_3.3SiO_2$) is a rare mineral found in the ejected masses of Monte Somma, Vesuvius. The properties of the mineral are defined as follows by Zambonini.[1] Tetragonal, hemihedral, $c=0.8861$; density 2.92 (2.936 Breithaupt, 2.932 Rammelsberg); uniaxial, positive, for sodium light $\omega=1.6035$, $\epsilon=1.6147$, $\epsilon-\omega=0.0112$.

Three analyses of sarcolite are available and are given below. Of these, the one by Scacchi seems to be of less value than the other two. A small amount of soda is given in all three analyses. It doubtless replaces lime (CaO) but has been considered in this paper as belonging to a theoretical soda sarcolite, $3Na_2O.Al_2O_3.3SiO_2$. It would make no difference for comparative purposes whether the soda were reduced to its equivalence of lime or whether, as is done in this paper, it were kept by itself as belonging to a distinct compound.

[1] Zambonini, F., Mineralogia Vesuviana, p. 247, 1910. Zambonini states that the optical properties given by Pauly (Centralbl. Mineralogie, 1906, p. 266) for sarcolite were in reality determined on some other mineral. Pauly gives $\omega=1.6404$, $\epsilon=1.6566$, for sodium light

The agreement of the analyses of sarcolite with the values calculated from its formula is shown below.

Comparison of analyses of sarcolite with calculated composition.

	Scacchi.[a]	Rammelsberg.[b]	Pauly.[c]	Calculated for $3CaO.Al_2O_3.3SiO_2$.
SiO_2	42.11	40.51	39.34	40.08
Al_2O_3	24.50	21.54	21.63	22.65
CaO	32.43	32.36	33.70	37.27
Na_2O	2.93	3.30	4.43	.....
K_2O	.....	1.20	.....	.....
MgO	.....	.....	.36	.....
	101.97	98.91	99.46	100.00

[a] Scacchi, A., Quadri Crystallographia, p. 66, Naples, 1842.
[b] Rammelsberg, C., Ueber die chemische Zusamensetzung einiger seltenen Mineralien des Vesuvs: Poggendorff's Annalen, vol. 109, p. 570, 1860.
[c] Pauly, A., Zur mikroskopischen Charakterisierung des Sarkolith: Centralbl. Mineralogie, 1906, p. 266.

The sarcolite from Vesuvius analyzed by Scacchi is composed of an isomorphous mixture of 7.2 per cent of soda sarcolite and 92.8 per cent of sarcolite. Calculated composition of this mixture is shown below.

Comparison of analysis of sarcolite by Scacchi with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	42.11	41.29	39.96	−1.33
Al_2O_3	24.50	24.03	22.58	−1.45
CaO	32.43	31.80	34.58	+2.78
Na_2O	2.93	2.88	2.88	.00
	101.97	100.00	100.00	.....

The differences are considerable and indicate that the analysis is not very exact or, more probably, that the sample analyzed was not pure and homogeneous.

The sarcolite from Vesuvius analyzed by Rammelsberg is composed of an isomorphous mixture of 10.5 per cent of soda sarcolite and 89.5 per cent of sarcolite. The analysis agrees fairly well with the calculated composition, as shown below.

Comparison of analysis of sarcolite by Rammelsberg with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	40.51	41.12	39.92	−1.20
Al_2O_3	21.54	21.87	22.56	+ .69
CaO	32.36	32.85	33.36	+ .51
Na_2O	3.30	4.16	4.16	.00
K_2O	1.20	.....	.....	.....
	98.91	100.00	100.00	.....

The sarcolite from Vesuvius analyzed by Pauly is composed of an isomorphous mixture of 2.6 per cent of åkermanite, 11.2 per cent of soda sarcolite, and 86.2 per cent of sarcolite. The agreement of the analysis with the calculated composition is good. A small admixture of åkermanite is introduced to account for the small amount of magnesia in the analysis.

Comparison of analysis of sarcolite by Pauly with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	39.34	39.56	40.09	+0.53
Al_2O_3	21.63	21.75	21.96	+ .21
CaO	33.70	33.88	33.14	− .74
Na_2O [a]	4.43	4.45	4.45	.00
MgO	.36	.36	.36	.00
	99.46	100.00	100.00	.....

[a] Trace of K_2O.

SODA SARCOLITE.

As stated under sarcolite, a soda sarcolite ($3Na_2O.Al_2O_3.3SiO_2$), corresponding in formula to sarcolite, has been assumed to be present in the sarcolites analyzed and also in nearly all the natural occurrences of the melilites and gehlenites. Its amount is never large, the maximum being 12.2 per cent in a melilite from Vesuvius analyzed by Damour. Most of the analyses show amounts less than 10 per cent. The reference of the soda to a compound of the sarcolite type is justified because sarcolite is the only naturally occurring end member of the melilite group containing soda. If no independent soda compound were assumed, an arbitrary assignment of the soda to either CaO or MgO would have to be made. The properties of soda sarcolite are not known, but its molecular weight (469) is so close to that of sarcolite (451) that their properties are doubtless very similar

ÅKERMANITE.

Åkermanite ($4MgO.8CaO.9SiO_2$), as a mineral, was identified by Zambonini [1] at Vesuvius. Its properties, as given by him, are as follows: Tetragonal, cleavages, 001 and 110; density, 3.12 (3.05 Freda); uniaxial, positive; for sodium light, $\omega = 1.6332$, $\epsilon = 1.639$, $\epsilon - \omega = 0.006$.

The two analyses reproduced in the subjoined table fully substantiate the formula $4MgO.8CaO.9SiO_2$. As shown below, the samples analyzed contained small amounts of the isomorphic mineral sarcolite, and if this is allowed for, the agreement with the formula is still closer.

Comparison of analyses of åkermanite with calculated composition.

	Analyses.[a]		Calculated for $4MgO.8CaO.9SiO_2$.
	Freda.	Zambonini.	
SiO_2	46.70	46.55	47.08
Al_2O_3	1.09	.96	.....
CaO	39.62	39.30	38.93
MgO	13.38	13.30	13.99
FeO	.....	.12	.....
	100.79	100.23	100.00

[a] Zambonini, F., Mineralogia Vesuviana, p. 255, 1910.

The åkermanite from Vesuvius analyzed by Freda is composed of an isomorphous mixture of 95.4 per cent of åkermanite and 4.6 per cent of sarcolite. The analysis agrees closely with the calculated composition.

Comparison of analysis of åkermanite by Freda with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	46.70	46.47	46.76	+0.29
Al_2O_3	1.09	.96	1.04	+ .08
CaO	39.62	39.23	38.86	− .37
MgO	13.38	13.34	13.34	.00
	100.79	100.00	100.00	.....

[1] Zambonini, F., Mineralogia Vesuviana, p. 255, 1910.

The åkermanite from Vesuvius analyzed by Zambonini is composed of an isomorphous mixture of 94.9 per cent of åkermanite and 5.1 per cent of sarcolite. This analysis also shows only slight differences from the calculated composition.

Comparison of analysis of åkermanite by Zambonini with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	46.55	46.33	46.72	+0.39
Al_2O_3	.96	1.08	1.16	+ .08
CaO	39.30	39.31	38.84	− .47
MgO	13.30	13.28	13.28	.00
FeO	.12	.....	.....	.....
	100.23	100.00	100.00	.....

The suggestion of Shepherd, Rankin, and Wright [1] that the correct formula for pure åkermanite is $3CaO.2SiO_2$ is not in agreement with the facts.

VELARDEÑITE.

The properties of velardeñite ($2CaO.Al_2O_3.SiO_2$), the third mineral species and primary compound which occurs in isomorphous mixture in the members of the melilite group, have already been described on page 107.

SUMMARY OF PROPERTIES OF PRIMARY COMPOUNDS.

For comparison and convenience, the properties of the primary compounds used in the following discussion of the isomorphous mixtures of two or more of the primary compounds are summarized in the following table:

Summary of properties of tetragonal primary compounds.

	Sarcolite.	Åkermanite.	Velardeñite.
Density	2.92	3.12	3.04
Optical sign	Positive.	Positive.	Negative.
ω	1.6035	1.6332	1.667
ϵ	1.6147	1.639	1.658
Birefringence	.0112	.006	.009

[1] Shepherd, E. S., and Rankin, G. A., Preliminary report on the ternary system $CaO-Al_2O_3-SiO_2$; a study of the constitution of Portland cement clinker, with optical study by F. E. Wright: Jour. Ind. and Eng. Chemistry, vol. 3, p. 224, 1911.

ISOMORPHOUS MIXTURES OF TWO OR MORE OF THE PRIMARY COMPOUNDS.

In the following pages all the reliable analyses of minerals of the melilite group (including gehlenite) have been tested to see whether their composition can be expressed as mixtures of the four primary compounds just given. It may be said, in advance, that with the exception of the iron-rich melilites from Capo di Bove and the one from Colorado, all the samples analyzed agree very well with the interpretation here given.

The literature previous to 1892 has not been searched, as the analyses given by Dana[1] have (with some exceptions) been taken. To these are added the analyses that have been published since 1892. Of the melilite analyses given by Dana only those by Damour could be utilized. Von Kobell's analysis, published in 1832, was omitted, as the original paper was not available and no proof could be had as to the purity of the sample analyzed. The last melilite analysis given by Dana was made by Schulze on a small amount of material, which was, moreover, contaminated with olivine, whence the high percentage of $MgO + FeO$.

It has also been necessary to disregard several of the gehlenite analyses. Dana's Nos. 4 and 5, published by Kühn[2] in 1846, have to be omitted, as reference to the original article showed that Kühn treated his material with very dilute acid to remove calcium carbonate and furthermore did not determine the state of oxidation of the iron. The figures for iron represent arbitrary assumptions. The two analyses by Janovsky[3] (Dana's Nos. 6 and 7) were both made on impure material, and No. 7 especially (not No. 6, as given by Dana) contained considerable mixed vesuvianite. No. 6 is stated to have contained vesuvianite but was considered much purer than No. 7.

It was decided to omit all analyses of artificial melilites, as these were for the most part accidentally formed and did not represent pure products. It would be difficult to determine the purity of some of the artificial melilites whose analyses have been published, and any assumptions as to the composition of the impurity would be so uncertain that the results derived from a consideration of analyses of artificial melilite would be of no value.

The comparison of the analyses of the natural minerals with the calculated composition has been simplified by combining several bases and then recalculating the original analyses to 100.00 per cent. Water and other foreign matter have been simply omitted.

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[1] Dana, E. S., System of mineralogy, 6th ed., pp. 475, 476, 1892.

[2] Kühn, O. B., Mineralanalysen; 4, Gehlenit: Annalen d. Chemie und Pharmacie (Wöhler und Liebig), Bd. 59, p. 371, 1846.

[3] Zepharovich, V., Mineralogische Mittheilungen: 2, Gehlenit von Oravicza: Akad. Wiss. Wien Sitzungsber., Bd. 69, Abth. 1, p. 26, 1874.

Ferric iron, as Fe_2O_3, has been recalculated to alumina (Al_2O_3). Ferric iron exists in large amount in the melilite from Capo di Bove, near Rome. In fact, the analyses of the brown melilite, the variety richest in Fe_2O_3, show a higher actual percentage of Fe_2O_3 than of Al_2O_3, but considered molecularly the iron does not exceed the Al_2O_3. In the analyses showing the greatest amount of iron the ratio of Fe_2O_3 to Al_2O_3 is almost exactly 1 : 1. Another primary component, namely, an iron-calcium silicate, should possibly have been introduced, but the number of components would then have become five and the expression of the interpretation would have been complicated considerably. The Fe_2O_3 has therefore been recalculated and combined with the Al_2O_3.

As Fe_2O_3 has not been determined to exist in notable quantity in any of the pure end members, it would furthermore be impossible to decide to which of the three end-member minerals it should be assigned. The compound $3CaO.Al_2O_3.3SiO_2$ (sarcolite) is polymorphous, for the formula represents that of grossularite as well as that of sarcolite. Now an iron-calcium garnet, $3CaO.Fe_2O_3.3SiO_2$, andradite, is a common mineral, and the ferric iron in melilites would naturally then be ascribed to the presence of a ferric iron sarcolite, $3CaO.Fe_2O_3.3SiO_2$. A recent paper by Scrivenor[1] describes an iron-calcium garnet which was "quickly and completely decomposed when reduced to powder and heated with hydrochloric acid, silica being liberated." The garnet was isotropic and showed very clearly the form of the rhombic dodecahedron. Crystals of sarcolite resemble those of the isometric system, and, as sarcolite is tetragonal, basal cleavage pieces would be isotropic. Could a ferric iron sarcolite ($3CaO.Fe_2O_3.3SiO_2$) have been present?

The remaining bases which in the recalculated analyses are to be added to other bases are few in number. K_2O naturally goes with Na_2O, and FeO and MnO have been added to MgO, CaO therefore standing by itself and not receiving any increment in the form of replacing bases. It is doubtful if much difference in the ratios would have been found if the FeO + MnO had been added to CaO. In silicates, however, it seems as if CaO on the one hand and FeO + MnO + MgO on the other hand exist as separate groups which do not replace each other.

The recalculated and reduced analyses may represent the original analyses inaccurately in that the combination of bases may not be correct; in that the omission of the water as such may be wrong, for the water may, in part at least, belong to an associated hydrous mineral; and in that the reduction to 100.00 per cent distributes an error in the determination of a single constituent over the whole analysis.

[1] Scrivenor, J. B., A calcium-iron garnet from China: Mineralog. Mag., vol. 17, p. 51, 1913.

The fact, however, that the following comparisons show a very close agreement indicates that perhaps these inaccuracies are not great.

The gehlenite from Velardeña[1] analyzed by Allen (quoted by Wright) is composed of an isomorphous mixture of 20 per cent of åkermanite, 0.7 per cent of soda sarcolite, and 79.3 per cent of velardeñite.

Comparison of gehlenite analysis by Allen with calculated composition[a] of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	26.33	26.99	27.10	+0.11
Al_2O_3	27.82	29.43	29.65	+ .22
CaO	39.55	40.50	40.17	− .33
Na_2O	.21	.29	.29	.00
MgO	2.44	2.79	2.79	.00
TiO_2	.03	.....	.....	.....
Fe_2O_3	1.43	.....	.....	.....
K_2O	.10	.....	.....	.....
FeO	.50	.....	.....	.....
MnO	.01	.....	.....	.....
H_2O	1.85	.....	.....	.....
	100.27	100.00	100.00	.....

[a] The reduced analysis and the calculated composition differ slightly from the values given on p. 107 simply because there the soda was combined with the lime, whereas here it is treated separately.

The gehlenite from Monzoni analyzed by Rammelsberg[2] is composed of an isomorphous mixture of 36.2 per cent of åkermanite and 63.8 per cent of velardeñite.

Comparison of gehlenite analysis by Rammelsberg with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	29.78	30.81	31.04	+0.23
Al_2O_3	22.02	24.91	23.73	−1.18
CaO	37.90	39.21	40.16	+ .95
MgO	3.88	5.07	5.07	.00
Fe_2O_3	3.22	.....	.....	.....
FeO	1.63	.....	.....	.....
MnO	.19	.....	.....	.....
Ignition by difference	1.38	.....	.....	.....
	100.00	100.00	100.00	.....

[1] This is the mineral called velardeñite. See p. 106.

[2] Dana, E. S., System of mineralogy, 6th ed., p. 476, 1892.

The gehlenite from Monzoni, analyzed by Lemberg,[1] is composed of an isomorphous mixture of 28.7 per cent of åkermanite, 15.7 per cent of sarcolite, and 55.6 per cent of velardeñite.

Comparison of gehlenite analysis by Lemberg with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	30.01	31.88	32.00	+0.12
Al_2O_3	21.33	25.08	24.24	− .84
CaO	36.74	39.03	39.75	+ .72
MgO	3.77	4.01	4.01	.00
Fe_2O_3	3.56	.....	.....	.....
Ignition	4.72	.....	.....	.....
	100.13	100.00	100.00	.....

The gehlenite from Monzoni analyzed by Damour[1] is composed of an isomorphous mixture of 16.4 per cent of åkermanite, 0.8 per cent of soda sarcolite, 38.1 per cent of sarcolite, and 44.7 per cent of velardeñite.

Comparison of analysis of gehlenite by Damour with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	31.60	32.97	33.09	+0.12
Al_2O_3	19.80	24.64	25.42	+ .78
CaO	38.11	39.76	38.86	− .90
Na_2O	.33	.34	.34	.00
MgO	2.20	2.29	2.29	.00
Fe_2O_3	5.97	.....	.....	.....
H_2O	1.53	.....	.....	.....
	99.54	100.00	100.00	.....

The melilite from Colorado analyzed by Schaller[2] is composed of an isomorphous mixture of 41.3 per cent of åkermanite, 8.7 per cent of soda sarcolite, and 50 per cent of sarcolite.

[1] Dana, E. S., op. cit., p. 476.

[2] Larsen, E. S., and Hunter, J. F., Melilite and other minerals from Gunnison County, Colo.: Washington Acad. Sci. Jour., vol. 4, p. 473, 1914.

Comparison of analysis of melilite by Schaller with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	42.07	44.56	42.85	+1.71
Al_2O_3	10.30	11.25	13.22	−1.97
CaO	35.41	34.98	34.72	+ .26
Na_2O	3.24	3.43	3.43	.00
MgO	4.15	5.78	5.78	.00
TiO_2	.20	.....	.....	.....
Fe_2O_3	.50	.....	.....	.....
FeO	2.18	.....	.....	.....
MnO	.16	.....	.....	.....
P_2O_5	.82	.....	.....	.....
CO_2	.90	.....	.....	.....
H_2O	.47	.....	.....	.....
K_2O	Trace.	.....	.....	.....
	100.40	100.00	100.00	.....

The melilite from Vesuvius analyzed by Damour [1] is composed of an isomorphous mixture of 42.5 per cent of åkermanite, 12.2 per cent of soda sarcolite, 34 per cent of sarcolite, and 11.3 per cent of velardeñite.

Comparison of analysis of melilite by Damour with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	40.69	42.11	40.77	−1.34
Al_2O_3	10.88	14.19	14.57	+ .38
CaO	31.81	32.92	33.88	+ .96
Na_2O	4.43	4.83	4.83	.00
MgO	5.75	5.95	5.95	.00
Fe_2O_3	4.43	.....	.....	.....
K_2O	.36	.....	.....	.....
	98.35	100.00	100.00	.....

The melilite from Capo di Bove analyzed by Bodlaender is composed of an isomorphous mixture of 42.5 per cent of åkermanite, 9.8 per cent of soda sarcolite, 41.2 per cent of sarcolite, and 6.5 per cent of velardeñite.

[1] Dana, E. S., op. cit., p. 476.

Comparison of analysis of melilite by Bodlaender with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	41.09	41.63	41.67	+0.04
Al_2O_3	10.93	13.28	13.89	+ .61
CaO	34.78	35.24	34.59	− .65
Na_2O	3.40	3.90	3.90	.00
MgO	5.87	5.95	5.95	.00
Fe_2O_3	3.40	.....	.....	.....
K_2O	.68	.....	.....	.....
H_2O	.24	.....	.....	.....
	100.39	100.00	100.00	.....

The yellow melilite from Capo di Bove analyzed by Damour [1] is composed of an isomorphous mixture of 49 per cent of åkermanite, 7.8 per cent of soda sarcolite, 33.7 per cent of sarcolite, and 9.5 per cent of velardeñite.

Comparison of analysis of yellow melilite by Damour with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	39.27	41.77	41.67	−0.10
Al_2O_3	6.42	13.75	12.86	− .89
CaO	32.47	34.54	35.53	+ .99
Na_2O	1.95	3.09	3.09	.00
MgO	6.44	6.85	6.85	.00
Fe_2O_3	10.17	.....	.....	.....
K_2O	1.46	.....	.....	.....
	98.18	100.00	100.00	.....

The yellow melilite from Capo di Bove analyzed by Zambonini [2] is composed of an isomorphous mixture of 49.5 per cent of åkermanite, 8.3 per cent of soda sarcolite, 32.4 per cent of sarcolite, and 9.8 per cent of velardeñite.

[1] Dana, E. S., op. cit., p. 476.

[2] Zambonini, F., Ueber eine krystallisierte Schlacke der Seigerhütte bei Hettstedt, nebst Bemerkungen über die chemische Zusammensetzung des Melilith: Zeitschr. Kryst. Min., vol. 41, p. 266, 1906.

Comparison of analysis of yellow melilite by Zambonini with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	40.14	41.93	41.63	−0.30
Al_2O_3	6.47	13.40	12.80	− .60
CaO	32.98	34.45	35.35	+ .90
Na_2O	2.18	3.30	3.30	.00
MgO	6.33	6.92	6.92	.00
Fe_2O_3	9.95	.....	.....	.....
FeO	.53	.....	.....	.....
K_2O	1.49	.....	.....	.....
H_2O	.27	.....	.....	.....
TiO_2,MnO	Trace.	.....	.....	.....
	100.34	100.00	100.00	.....

The brown melilite from Capo di Bove analyzed by Damour[1] is composed of an isomorphous mixture of 50.3 per cent of åkermanite, 8.2 per cent of soda sarcolite, 26.5 per cent of sarcolite, and 15 per cent of velardeñite.

Comparison of analysis of brown melilite by Damour with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	38.34	40.26	40.73	+0.47
Al_2O_3	8.61	15.77	13.37	−2.40
CaO	32.05	33.65	35.58	+1.93
Na_2O	2.12	3.28	3.28	.00
MgO	6.71	7.04	7.04	.00
Fe_2O_3	10.02	.....	.....	.....
K_2O	1.51	.....	.....	.....
	99.36	100.00	100.00	.....

The brown melilite from Capo di Bove analyzed by Zambonini[2] is composed of an isomorphous mixture of 47.9 per cent of åkermanite, 8.3 per cent of soda sarcolite, 28 per cent of sarcolite, and 15.8 per cent of velardeñite.

[1] Dana, E. S., op. cit., p. 476.
[2] Zambonini, F., op. cit., p. 266.

Comparison of analysis of brown melilite by Zambonini with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	39.20	40.93	40.42	−0.51
Al_2O_3	7.56	15.47	14.05	−1.42
CaO	32.18	33.60	35.53	+1.93
Na_2O	2.21	3.31	3.31	.00
MgO	6.41	6.69	6.69	.00
Fe_2O_3	11.34	.....	.....	.....
K_2O	1.45	.....	.....	.....
H_2O	.21	.....	.....	.....
TiO_2,MnO	Trace.	.....	.....	.....
	100.56	100.00	100.00	.....

The main difference between the calculated composition and the reduced analyses shown in the last two tables is that in the calculated composition Al_2O_3 is too low and CaO too high. The two analyses of brown melilite from Capo di Bove both show a large amount of Fe_2O_3 and no FeO. It seems possible that a part of the iron in these melilites may exist as FeO but had become oxidized, possibly by fine grinding, so that the determination of Fe_2O_3 as given in the analysis is too high. A readjustment on such a basis would give results agreeing much closer with the calculated composition than the actual analysis does.

The fuggerite from Monzoni analyzed by E. Mayr[1] is composed of an isomorphous mixture of 35.3 per cent of åkermanite, 5.2 per cent of soda sarcolite, 16 per cent of sarcolite, and 43.5 per cent of velardeñite.

Comparison of analysis of fuggerite with calculated composition of isomorphous mixture.

	Original analysis.	Analysis reduced.	Calculated.	Difference.
SiO_2	34.04	34.45	34.59	+0.14
Al_2O_3	17.97	20.45	20.93	+ .48
CaO	37.65	38.10	37.48	− .62
Na_2O	2.04	2.06	2.06	.00
MgO	4.89	4.94	4.94	.00
Fe_2O_3	3.49	.....	.....	.....
Insoluble	.12	.....	.....	.....
K_2O, MnO	Trace.	.....	.....	.....
	100.20	100.00	100.00	.....

[1] Weinschenk, E., Fuggerit, ein neues Mineral aus dem Fassathal: Zeitschr. Kryst. Min., vol. 27, p. 577, 1896.

COMPOSITION OF THE MIXTURES.

In order to show more clearly the relations of the minerals whose composition has been discussed on the previous pages, the 17 mineral analyses have been plotted on a triangular plan with the three minerals åkermanite, sarcolite, and velardeñite as the three apices (fig. 89). The percentages of sarcolite and soda sarcolite have been added together, a procedure justified by the nearly equal molecular weight of the two compounds. (Compare p. 115.)

The mineral compositions as plotted on figure 89 are summarized below, with the same numbering as used in the diagram.

Summary of mineral composition of members of the melilite group, graphically shown in figure 89.

No.	Mineral.	Locality.	Author.	Åkermanite.	Sarcolite.	Velardeñite.
1	Sarcolite	Vesuvius	Scacchi	0	100	0
2	do	do	Rammelsberg	0	100	0
3	do	do	Pauly	2.6	97.4	0
4	Åkermanite	do	Freda	95.4	4.6	0
5	do	do	Zambonini	94.9	5.1	0
6	Gehlenite (velardeñite).	Velardeña, Mexico.	Wright	20.0	.7	79.3
7	Gehlenite	Vesuvius	Rammelsberg	36.2	.0	63.8
8	do	do	Lemberg	28.7	15.7	55.6
9	do	do	Damour	16.4	38.9	44.7
10	Melilite	do	do	42.5	46.2	11.3
11	do	Capo di Bove, Italy.	Bodlaender	42.5	51.0	6.5
12	Yellow melilite	do	Damour	49.0	41.5	9.5
13	do	do	Zambonini	49.5	40.7	9.8
14	Brown melilite	do	Damour	50.3	34.7	15.0
15	do	do	Zambonini	47.9	36.3	15.8
16	Melilite	Colorado	Larsen and Hunter.	41.3	58.7	0
17	Fuggerite	Fassathal	Weinschenk	35.3	21.2	43.5

The "gehlenites" have a varying composition, as is clearly shown in figure 89, and do not all correspond to the simple formula $3CaO.Al_2O_3.2SiO_2$, as has been advocated. Together with those of velardeñite and fuggerite, however, their symbols lie in the velardeñite portion of the triangle, and, like velardeñite, all the "gehlenites" are optically negative. They represent isomorphous mixtures of the three minerals, in which the negative velardeñite occurs in greater amount than either of the other two. The properties of fuggerite as given by Weinschenk are not accurately in accord with those of the other gehlenites, and the fact that the symbol of a double salt with properties differing from those of velardeñite, åkermanite, or sarcolite falls in this part of the diagram may explain the unusual properties shown by fuggerite.

Now, if, as has been suggested by the chemical composition, melilite is essentially an isomorphous mixture of åkermanite and sarcolite (all the melilites contain over 80 per cent of åkermanite and sarcolite), both of which are optically positive, then the melilites should likewise be positive. In fact melilites are mostly negative, though occasionally a positive one is seen. Melilites which are almost isotropic have also been described.

The plotted analyses of melilite are confined to a small portion of the triangular field (fig. 89), although out of seven analyses only three localities are included. The melilite from Colorado is apparently the

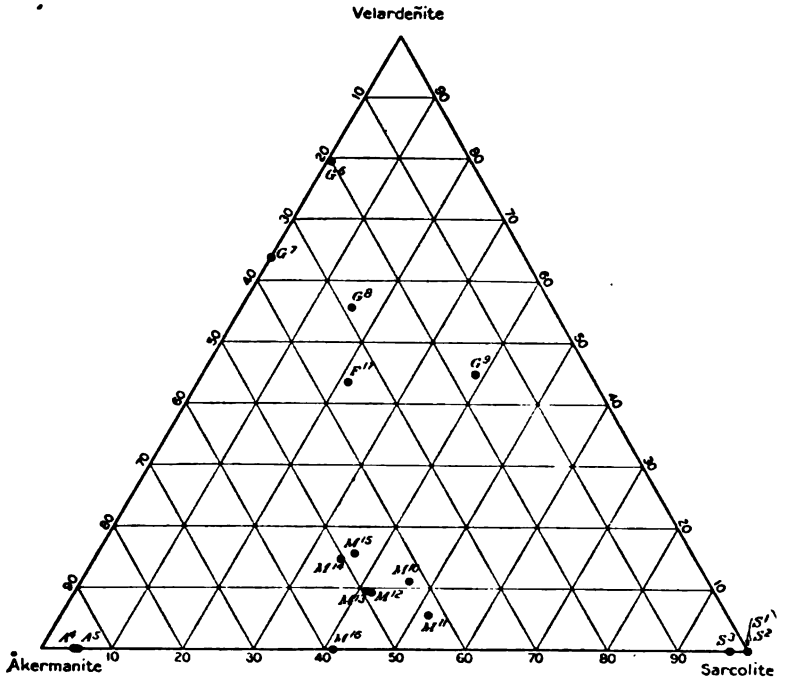


FIGURE 89.—Triangular representation of the chemical composition of minerals of the melilite group, including åkermanite (*A*), sarcolite (*S*), velardeñite (G^8), melilite (*M*), gehlenite (G^7 to G^9), and fuggerite (*F*).

simplest in composition, for it is composed of only two end members, sarcolite and åkermanite. It is to be noted, however, that the agreement of the analysis with the calculated composition, as given on page 122, is not very close. Over 84 per cent of the other melilites consist of sarcolite and åkermanite. Now, both these two minerals are optically positive, whereas melilite is generally negative, although positive varieties are known.

Two explanations suggest themselves to explain the apparent discrepancy. One is that an isomorphous mixture of two optically positive substances is not necessarily of the same sign throughout, for

the sign depends on the relative values of the refractive indices. For positive minerals, ϵ is greater than ω, but for negative minerals it is less. If the refractive indices of all isomorphous mixtures of sarcolite and åkermanite are linear functions of their composition, then negative melilite can not be such a simple isomorphous mixture. On the other hand, if the indices are not linear functions of the composition, then negative melilites may be isomorphous mixtures of two positive minerals, the refractive indices changing with the composition, as shown in figure 90. If some such relation held good, then most melilites would be negative, a smaller number would be positive, and a

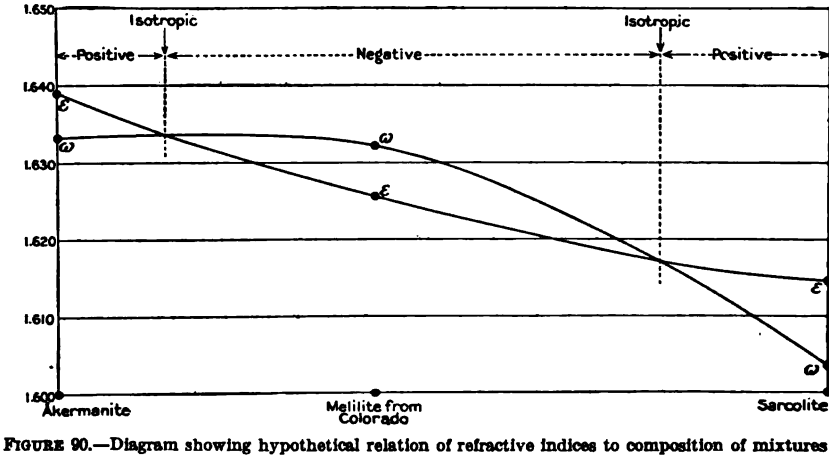


FIGURE 90.—Diagram showing hypothetical relation of refractive indices to composition of mixtures of åkermanite and sarcolite.

very small number would be isotropic. With relations as shown in figure 90, there are two mixtures (about 14 per cent and 79 per cent of åkermanite) which are isotropic.

A second explanation, however, deserves careful consideration, although at present its possibility can only be suggested. It is dependent on the existence of a double compound of åkermanite and sarcolite which would be optically negative, and the melilites would consist essentially of this double compound with smaller amounts of åkermanite, sarcolite, and velardeñite in solid solution.

The concentration of the symbols representing the melilite analyses in a small portion of the field (fig. 89) is in a way somewhat suggestive of the existence of a double compound.

THE COMPOSITION OF CEBOLLITE.

Cebollite, an alteration product of melilite, was found near Cebolla Creek, Gunnison County, Colo., and as described by Larsen[1] forms compact masses of a fibrous character. The mineral is probably orthorhombic, biaxial, positive, $\alpha = 1.595 \pm 0.003$, $\beta = 1.60$, $\gamma = 1.628 \pm 0.005$. It resembles the zeolites in its properties and composition. Hardness = 5, specific gravity = 2.96.

The mineral gelatinizes with acids and gives off water when heated in a closed tube. An analysis of a sample containing as little as possible of the associated insoluble diopside and garnet gave the following results:

Analysis and ratios of cebollite.

	Analysis.	Insoluble deducted.	Ratios.		
Insoluble[a]	18.05	.....			
Soluble in HCl:					
SiO	27.06	33.02	0.550		3.26 or 3×1.09
Al_2O_3	11.49	14.02	.137	.158	0.94 or 1×0.94
Fe_2O_3	2.81	3.43	.021		
CaO	29.27	35.72	.638		
FeO	.17	.21	.003	.799	4.74 or 5×0.95
MgO	3.84	4.69	.117		
Na_2O	2.10	2.57	.041		
H_2O+	5.13	6.26	.348		2.06 or 2×1.03
H_2O-	.00	.....			
TiO_2, K_2O	Trace.	.....			
	99.92	99.92			

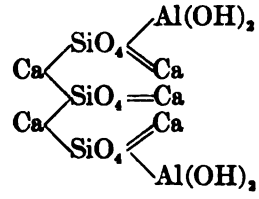
[a] Diopside and garnet.

The formula derived from the analysis is $3SiO_2.Al_2O_3.5R''O.2H_2O$, in which R'' is chiefly Ca with smaller amounts of Mg and Na_2. The ratio of $Na_2O : MgO + FeO : CaO$ is 1 : 3 : 16. Considering all the R''O as CaO, the formula, $Si_3Al_2Ca_5H_4O_{16}$, may be written in two ways—$(SiO_4)_3.Ca_5.[Al(OH)_2]_2$ or $(SiO_4)_3.(CaOH)_4.Ca.Al_2$.

The powdered mineral, treated with water, does not show an alkaline reaction with phenolphthalein, and if for certain minerals such a reaction indicates the presence of the CaOH group, as is suggested on page 154, the second of the formulas above given

[1] Larsen, E. S., and Schaller, W. T., Cebollite, a new mineral; Washington Acad. Sci. Jour., vol. 4, p. 480, 1914.

becomes untenable, and the formula of cebollite is consequently $(SiO_4)_3.Ca_5.[Al(OH)_2]_2$, which can be written structurally as follows:



The cebollite seems to belong to the zeolite group, although the presence of several per cent of magnesium is unusual.

THE CRYSTALLOGRAPHY OF THAUMASITE.

Several specimens of thaumasite from the well-known locality at West Paterson, N. J., showed well-developed crystals which reached a maximum length of about 5 millimeters. The crystals are hexagonal and consist of the prism $m\{10\bar{1}0\}$ and the base $c\{0001\}$. They show gradations from a short prismatic habit (fig. 91) to a long prismatic habit (fig. 92). Although well-formed single crystals are

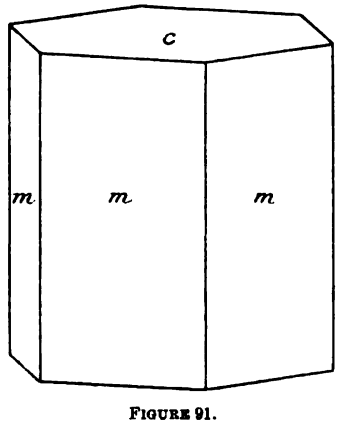


FIGURE 91.

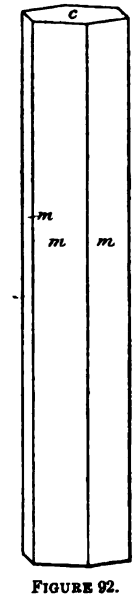


FIGURE 92.

FIGURE 91.—Short prismatic crystal of thaumasite.
FIGURE 92.—Long prismatic crystal of thaumasite.

not rare, many of them are composed of one or more large units, to which several smaller crystals are attached. These smaller crystals are either in parallel position or deviate slightly from strict parallelism, as is shown in figure 93, which represents such a group as it appeared under the microscope. The crystals are striated vertically.

A single terminated crystal was found and measured. It is shown in ideal development in figure 94. The forms present are m, c, and $p\{10\bar{1}1\}$. The ρ angles of the pyramid faces, of which only four could be measured, are 53°30′, 51°30′, 50°15′, and 50°45′; average 51°30′, from which the c axis is calculated to be 1.09.

The prism faces, although striated and built up of several faces, not all of which were in parallel position, were bright and gave good reflections. Their interfacial angle seldom measured more than a degree different from 60°. The base is always dull and gave no reflection. The pyramid faces were likewise dull and could be measured only by means of maximum illumination.

The same crystal which showed the faces of p also had a minute face whose ρ angle was 31°40′. On a different crystal a face was

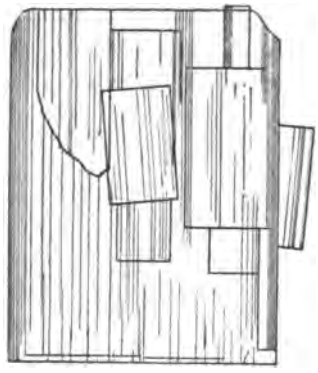


FIGURE 93.

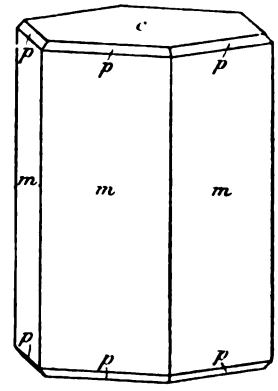


FIGURE 94.

FIGURE 93.—Compound crystal of thaumasite, with attached smaller crystals, as seen under the microscope.

FIGURE 94.—Terminated crystal of thaumasite. Forms: $m\{10\bar{1}0\}$, $c\{0001\}$, $p\{10\bar{1}1\}$.

measured whose ρ angle was 31°41′ and on a third crystal two faces gave ρ angles of 31°45′ and 31°53′. The ϕ angles varied so much for these different faces that the position of the form could not be determined, although the faces measured may not belong to a definite form, yet it would seem remarkable to find faces on three different crystals which would give the same ρ angle.

Qualitative tests on a small sample of the selected crystals showed that they were thaumasite.

THE CHEMICAL COMPOSITION OF TREMOLITE.

In a recent paper Allen and Clement[1] have suggested that the water in tremolite is "not chemically combined, although the mineral in the powdered state is not completely dehydrated under 900°. It is to be regarded as dissolved water, and tremolite as a solid solution. * * * Diopside and tremolite seem to give off their water continuously, but not indefinitely, with rising temperatures, though it is quite possible the curves represent cases of false equilibria."

According to their view, then, the mineral tremolite, as found in nature, represents a chemical compound + water. The water present would not be a necessary inherent part of the mineral, and the true composition of the mineral would be shown by the analysis with the water excluded. This conclusion the authors reached as a result of finding that "the water in all the specimens is lost gradually as the temperature rises, without any sudden change of properties or loss of homogeneity. It can not, therefore, be chemically combined, even though it is given off so very slowly at a temperature of 900°."

It seems probable, however, that a different explanation may be offered from that which contends that the water in tremolite is dissolved and not a true part of the mineral. A similar conclusion was reached by Coblentz[2] as a result of experiments based on the absorption spectrum of water in minerals. He said: "From the present data it is evident that the water in tremolite is not present in the same condition as in other substances containing water in solid solution or dissolved water. * * * From the present data it appears that in tremolite the water is constitutional, with possible OH groups, the small band at 2.95 μ being complex, as in the other hydroxides just cited [brucite, diaspore, bauxite, göthite]. This is, of course, contrary to the vapor-pressure experiments; but it is the most satisfactory conclusion to be drawn from the present experiments."

The zeolites have often been cited as examples of minerals in which the water is not chemically combined, but Beutell and Blaschke[3] have recently contended that the water in stilbite is chemically combined, and they further question whether it has been proved that for any hydrosilicate the water is dissolved or absorbed.

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[1] Allen, E. T., and Clement, J. K., The rôle of water in tremolite and certain other minerals: Am. Jour. Sci., 4th ser., vol. 26, p. 101, 1908.

[2] Coblentz, W. W., The rôle of water in minerals: Franklin Inst. Jour., vol. 172, p. 334, 1911.

[3] Beutell, A., and Blaschke, K., Das Wasser im Desmin ist chemisch gebunden: Centralbl. Mineralogie, 1915, pp. 4–11; Ist die Existenz krystallisierter Hydrosilicate mit gelöstem oder absorbiertem Wasser erwiesen? : Idem, pp. 195–200.

Together with their experimental data, Allen and Clement give five analyses of tremolite which have not heretofore been accorded the attention they deserve, for not only were the samples carefully selected and purified, but the analytical work was done by a skilled analyst of the highest grade. The five analyses of tremolite are reproduced below.

Analyses of tremolite.

[E. T. Allen, analyst.]

	1 Ham Island, Alaska.	2 Ossining, N. Y.	3 Gouverneur, N. Y.	4 Russell, N. Y.	5 Edwards, N. Y.
SiO_2	58.59	57.35	56.92	56.36	58.24
TiO_2	.....	.07	.10	.06	.04
Al_2O_3	.10	1.21	1.65	1.88	.60
Fe_2O_3	.....	.11	.36	.61	.43
FeO	.....	.23	None.	1.01	None.
MnO	.....	.01	.....	.04	1.28
MgO	24.78	23.87	23.81	22.97	25.16
CaO	13.95	14.02	12.51	12.82	10.85
Na_2O	.12	.42	1.22	.94	.82
K_2O	.10	.19	.60	.74	.19
H_2O	2.31	2.21	2.01	1.72	2.50
F	None.	.11	1.03	1.23	.24
	99.95	99.80	100.21	100.38	100.35
$O=F_2$	.00	.05	.43	.53	.10
	99.95	99.75	99.78	99.85	100.25

Assuming that fluorine and hydroxyl replace each other and adding together the percentages of water (H_2O, equivalent to 2OH) and one-half the percentages of fluorine (since F is equivalent to OH, F_2 becomes equivalent to 2OH or H_2O), we obtain the following percentages of water plus fluorine for the five tremolite analyses: 2.31, 2.27, 2.53, 2.34, 2.62. These figures surely denote a constant quantity for a mineral which is a member of a large isomorphous group.

The ratios were calculated from the analyses just given. Titanium as TiO_2 is combined with silica (SiO_2), Fe_2O_3 with Al_2O_3, MnO with FeO, K_2O with Na_2O, and F_2 with H_2O.

Ratios of tremolite analyses.

	1	2	3	4	5
SiO_2	0.971	0.952	0.945	0.936	0.967
MgO	.615	.592	.591	.570	.624
CaO	.249	.250	.223	.229	.193
H_2O	.128	.126	.139	.128	.145
Al_2O_3	.001	.013	.018	.022	.009
FeO	.....	.003	.....	.014	.018
Na_2O	.003	.009	.026	.023	.015

If all these bases are combined on an assumption of equal valence—that is, $RO = MgO + CaO + H_2O + FeO + \frac{1}{3}Al_2O_3$—the following results are obtained:

Comparison of ratios of total bases to silica in tremolite.

	1	2	3	4	5
RO	0.995	0.984	0.985	0.971	0.998
SiO_2	.971	.952	.945	.936	.967
$\frac{RO}{SiO_2}$	1.02	1.03	1.04	1.04	1.03
$RO-H_2O$	.867	.858	.846	.843	.853
$\frac{RO-H_2O}{SiO_2}$	.89	.90	.89	.90	.88

This table shows conclusively that if all the MgO, CaO, Al_2O_3, Fe_2O_3, FeO, MnO, Na_2O, K_2O, H_2O, and F_2 are considered as forming the base of the chemical compound of which SiO_2 ($+TiO_2$) is the acid, then the ratio of base to acid is 1 : 1, as it should be in tremolite. That the ratio of the bases is very slightly above 1 is doubtless due to the fact that the summation of the bases includes a maximum number of ten constituents. The chance of foreign material (dust, impurities in reagents, etc.) being added during the analysis is very much greater for these ten bases than for the single acid (SiO_2).

From the above table it can also be seen that if water (plus fluorine) is excluded from consideration, then the ratio of the bases to the acid, $\frac{RO-H_2O,}{SiO_2}$ falls short of unity.

The same results can be shown by arbitrarily changing the ratio of silica (SiO_2) to 8.00 and recalculating the bases accordingly, as shown below:

Recalculated ratios of tremolite analyses.

	1	2	3	4	5
SiO_2	8.00	8.00	8.00	8.00	8.00
MgO	5.07	4.97	5.00	4.87	5.16
CaO	2.05	2.10	1.89	1.96	1.60
MO [a]	.02	.13	.27	.38	.30
H_2O [b]	1.07	1.06	1.18	1.09	1.20

[a] Includes FeO, MnO, Na_2O, K_2O, $\frac{1}{3}(Al_2O_3)$, $\frac{1}{3}(Fe_2O_3)$. [b] Includes fluorine as (F_2).

Obviously the ratios of $MgO + CaO + MO$ do not suffice to satisfy the eight parts of silica, and without the water the composition of the mineral is incomplete, unless so complex and improbable a formula as $7RO.8SiO_2$ or $9RO.10SiO_2$ is assumed for tremolite.

The constituents of MO can be so distributed between MgO and CaO, which they obviously replace, as to make the ratios of SiO_2: MgO : CaO : H_2O come very close to 8 : 5 : 2 : 1 and it is suggested that the formula for tremolite is $8SiO_2.5MgO.2CaO.H_2O$ and not $3MgO.CaO.4SiO_2$, as given in the textbooks.

From the chemical side, it seems at least doubtful whether the conclusion of Allen and Clement is correct, and the writer suggests, in accordance with the conclusions of other authors (earlier cited), that the water in tremolite may be different from "dissolved water."

NEW OCCURRENCES OF SOME RARE MINERALS.

It seems advisable to put on record the identifications of some rare minerals which have been sent to the Geological Survey within the last few years.

A specimen of massive guanajuatite was sent by Mr. John E. Erickson from Salmon, Idaho. No mention of any other locality than the original one at Guanajuato, Mexico, could be found in the literature, so that the Idaho occurrence would make the second locality for this rare bismuth selenide.

Well-crystallized jarosite, in hexagonal scales reaching a diameter of 1 millimeter, was found in the Shattuck-Arizona copper mine at Bisbee, Ariz, and were sent in by Mr. Philip D. Wilson, of Bisbee. The brilliant crystals lie on massive iron oxide (hematite) and show only the base $c\{0001\}$ and the rhombohedron $r\{10\bar{1}1\}$. The angle $c:r$ was measured as 53° 19′, but the measurements were poor and not very reliable. Most of the crystals are uniaxial, negative; several of them show, in basal section, a division into six biaxial sectors (compare fig. 88) with the axial plane parallel to the edge *cr*. The measured angle 53° 19′, between that of jarosite (55° 16′) and natrojarosite[1] (51° 53′), suggested that the mineral from Bisbee might lie chemically between jarosite and natrojarosite, but qualitative tests showed that although a little soda was present potash was the predominant alkali.

Some rock specimens, sent in by Mr. George W. Davies, of Topaz, Cal., are thickly coated with brilliant yellow to orange greenockite.

[1] Compare table given by Hillebrand, W. F., and Penfield, S. L., Some additions to the alunite-jarosite group of minerals: U. S. Geol. Survey Bull. 262, p. 40, 1905.

GIGANTIC CRYSTALS OF SPODUMENE.

The occurrence of gigantic crystals of spodumene in the Black Hills of South Dakota has been known for some time and has been several times referred to in the literature. Blake,[1] as early as 1885, wrote: "One crystal which extends horizontally parallel with a drift is 36 feet in length in a straight line, and is from 1 to 3 feet in thickness. * * * Crystals from 5 to 20 feet long are numerous and incline in all directions." Hess[2] mentions a crystal that measured "42 feet in length, with a cross section of approximately 3 by 6 feet. Part was decayed and useless, but about 37 tons of spodumene was mined from it."

Ziegler[3] describes, in part, the immense size of the spodumene crystals as follows:

> The crystals are often of enormous size. In the Etta mine, where they are best exposed both in the open cut and in the tunnel, they frequently attain a diameter of 3 to 4 feet and a length of 30. The largest "log" so far found was 42 feet long and of 5 feet 4 inches maximum diameter. This one log alone would yield 90 tons of spodumene.

Two photographs of such gigantic crystals are shown in Plate V. The upper picture, taken by Mr. S. C. Smith at the Etta mine, near Keystone, in 1904, shows the largest "log," as these crystals are called, which had been uncovered up to that time of which Mr. Smith had any record. The length of the exposed portion, calculated from the photograph, is 47 feet. In Plate V, *B*, two molds of such large crystals are shown. The length of each of these molds, measured by the writer in 1904, was 40 feet, and the thickness varied from 2½ to 3 feet. In another part of the mine was seen a spodumene log whose exposed length was 25 feet and whose diameter was from 3 to 3½ feet.

These spodumene logs rarely contain any other mineral included as impurity. On a few crystals small amounts of quartz were seen, and more rarely minute amounts of cassiterite or strüverite occur embedded in the spodumene or form small veins therein. The spodumene cleaves readily and as mined is broken up into blocks about a foot in diameter. A layer of some alteration product, several inches thick, coats many of the crystals. It has been estimated that 25 tons of waste rock have to be removed in the extraction of 1 ton of spodumene.

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[1] Blake, W. P., Spodumene crystals of gigantic size: Am. Jour. Sci., 3d ser., vol. 29, p. 71, 1880.

[2] Hess, F. L., Lithium: U. S. Geol. Survey Mineral Resources, 1909, Part II, pp. 649-653, 1911.

[3] Ziegler, V., The mineral resources of the Harney Peak pegmatites—II; Min. and Sci. Press, vol. 108, p. 654, Apr. 18, 1914.

A. LARGEST CRYSTAL MINED UP TO 1904.

Photograph furnished by S. C. Smith.

B. MOLDS OF TWO IMMENSE CRYSTALS.

GIGANTIC CRYSTALS OF SPODUMENE, ETTA MINE, BLACK HILLS, S. DAK.

THE PROBABLE IDENTITY OF MARIPOSITE AND ALURGITE.

A comparison of the two analyses of mariposite made by Hillebrand[1] with Penfield's analysis[2] of alurgite shows that the two minerals are probably identical, as can be seen by the following table:

Comparison of analyses of mariposite and alurgite.

	Alurgite (Penfield).	Mariposite (Hillebrand).	
		White.	Green.
SiO_2	53.22	56.79	55.35
TiO_2	.....	[a] .18	.18
Al_2O_3	21.19	[a] 25.11	25.62
Fe_2O_3	1.22	[b] .63	.63
Cr_2O_3	.87	None.	.18
FeO	.....	[b] .92	.92
MnO	.18	.....	.....
MgO	6.02	3.29	3.25
CaO	.....	.07	.07
Na_2O	.34	[c] .17	[c] .12
K_2O	11.20	8.92	9.29
H_2O	5.75	4.72	4.52
	99.99	[d] 100.80	100.13

[a] The $Al_2O_3+TiO_2$ is given by Hillebrand as 25.29 per cent.
[b] The total iron oxides are given by Hillebrand as 1.59. The ferrous and ferric oxides were not separately determined. As the total sum of $FeO+Fe_2O_3$ in the green mariposite is 1.55 per cent, or nearly the same as in the white mariposite, the values for FeO and Fe_2O_3 in the white are taken from those given for the green.
[c] Includes Li_2O.
[d] The summation in Hillebrand's publication is 100.84.

A better comparison can be made by omitting the TiO_2, adding molecularly the Fe_2O_3, Cr_2O_3, and Mn_2O_3 to the Al_2O_3, the FeO, MnO, and CaO to the MgO, and the Na_2O to the K_2O, and then reducing the analyses to 100 per cent.

Recalculated analyses of mariposite and alurgite.

	Alurgite.	White mariposite.	Green mariposite.
SiO_2	53.58	56.76	55.74
Al_2O_3	22.69	25.49	26.32
MgO	6.16	3.85	3.84
K_2O	11.78	9.18	9.54
H_2O	5.79	4.72	4.56
	100.00	100.00	100.00

[1] Hillebrand, W. F., Mineralogical notes: U. S. Geol. Survey Bull. 167, p. 74, 1900.
[2] Penfield, S. L., On some minerals from the manganese mines of St. Marcel, in Piedmont, Italy: Am. Jour. Sci., 3d ser., vol. 46, p. 288, 1893.

The ratios calculated from these analyses, with SiO_2 taken arbitrarily as 12.00, are as follows:

Ratios of analyses of alurgite and mariposite.

	Alurgite.	White mariposite.	Green mariposite.
SiO_2	12.00	12.00	12.00
Al_2O_3	2.99	3.18	3.34
MgO	2.08	1.21	1.23
K_2O	1.69	1.24	1.31
H_2O	4.38	3.34	3.29

In alurgite the ratios become simple if the water (H_2O) and potash (K_2O) are taken together, for then the ratios yield the formula $12SiO_2.3Al_2O_3.2MgO.6(H_2,K_2)O$. The ratios of the green mariposite, which show greater divergence from the alurgite formula than the ratios of the white mariposite, indicate that the mariposite micas represent a solid solution of which one end member is represented by alurgite but of whose other end member no representative has as yet been found. The trend of the ratios would indicate some such formula as $12SiO_2.4Al_2O_3.K_2O.3H_2O$ for the second end member.

The physical and optical properties of these minerals, so far as determined, show a close relation, as is indicated by the following comparison:

Comparison of properties of alurgite and mariposite.

	Alurgite.	Mariposite.
Density	2.835–2.849	2.787, 2.817.
Pleochroism	Not very marked	Not perceptible.
Birefringence	Rather strong	Brilliant polarization colors, like talc.
Optical sign	Negative	Negative.
Axial angle ($2E$)	Biaxial and uniaxial (due to twinning) $2E=0°-57°$.	Uniaxial.
Mean index	1.594	1.63.

The name alurgite was proposed (in 1865) three years before the name mariposite (in 1868). Moreover, the first analysis of alurgite was published (in 1893) a few years before those of mariposite (1895). The name alurgite therefore clearly has priority.

THE AMBLYGONITE GROUP OF MINERALS—FREMONTITE (=NATRAMBLYGONITE).

It has long been recognized that both a fluophosphate and a hydroxyphosphate of aluminum and lithium have been placed together under the name of amblygonite. Descloizeaux separated the two species in his Manuel de minéralogie, but Dana, in the sixth edition of the System of mineralogy, grouped them together under the common name amblygonite, although he clearly stated the difference in their properties.

A consistent, systematic treatment of mineral species necessitates the separation of what is called amblygonite into two distinct species, and Penfield's analyses [1] sufficiently indicate the existence of both a fluo-compound and a hydroxy-compound with many intermediate mixtures.

A few years ago the writer [2] described a new mineral which was in fact the soda equivalent of amblygonite, and in order to emphasize this point the new mineral was named natramblygonite. This name, however, being half Greek and half Latin, is objectionable. (Compare the section "Nomenclature" in Dana's System of mineralogy, 6th edition, page xliii, No. 11.) A further objection to the name is found in the fact that in German it becomes "Natronamblygonit," a word that also means a "sodic amblygonite," which is not the intended meaning of "natramblygonite." A still further objection to the name is voiced by Gonnard,[3] who justly states that the mineral should have been called natromontebrasite, inasmuch as the water, considered as hydroxyl, is present in nearly twice the amount of the fluorine.

In view of these facts, it is considered best to withdraw the name natramblygonite and to substitute for it the name fremontite, after Fremont County, Colo., in which the mineral was found.

Fremontite, then, is a hydrophosphate of aluminum and sodium, with the formula $Na(AlOH)PO_4$. The only published analysis of fremontite shows a partial replacement of the sodium by lithium and of the hydroxyl by fluorine.

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[1] Dana, E. S., System of mineralogy, 6th ed., p. 782, 1892.

[2] Schaller, W. T., Natramblygonite, a new mineral: Am. Jour. Sci., 4th ser., vol. 31, p. 48, 1911.

[3] Gonnard, F., Soc. fraç. minéralogie bull., vol. 36, p. 120, 1913.

The amblygonite group consists of the following definite species, which very rarely occur in a pure state but whose mixture has been found at numerous localities:

Amblygonite, $Li(AlF)PO_4$ or $Li_2O.Al_2O_3.P_2O_5.F_2$.[1]
Montebrasite, $Li(AlOH)PO_4$ or $Li_2O.Al_2O_3.P_2O_5.H_2O$.
Fremontite, $Na(AlOH)PO_4$ or $Na_2O.Al_2O_3.P_2O_5.H_2O$.
Durangite,[2] $Na(AlF)AsO_4$ or $Na_2O.Al_2O_3.As_2O_5.F_2$.[1]

[1] Minus 1 atom of oxygen.
[2] The crystallographic relations of durangite with amblygonite are not yet clear.

THE CRYSTALLOGRAPHY OF FREMONTITE.

The original material of fremontite did not show any crystal form, and its crystallographic relation to amblygonite could only be inferred. The optical properties did not indicate any variance from the symmetry of amblygonite.

With zealous interest Mr. J. D. Endicott, of Canon City, Colo., continued development of the pegmatite in which the fremontite was found and procured a number of large crystals of that mineral. The best ones seen are in the collection of the late Mr. A. F. Holden, of Cleveland, Ohio, now in Harvard University, and through the kindness of Mr. Holden the writer was permitted to study and describe the crystals.

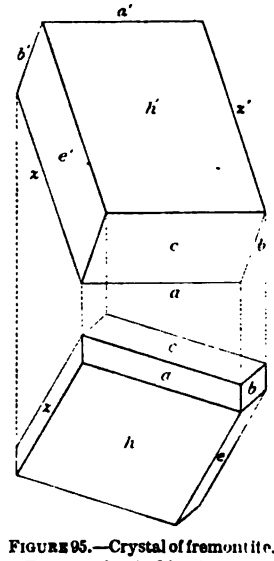

FIGURE 95.—Crystal of fremontite. Forms: $c\{001\}$, $b\{010\}$, $a\{100\}$, $z\{1\bar{2}0\}$, $h\{\bar{1}01\}$, $e\{0\bar{2}1\}$.

The smallest crystal is completely developed and is described below. Two specimens of pegmatite contain larger crystals built up of several individuals in parallel position. Both of the larger crystals are similar in combination and habit to the smaller one and are therefore not further described.

The small crystal is thick tabular in habit and is shown in projection in figure 95. The dimensions of the crystal are 35 by 28 by 13 millimeters. The faces are all dull and uneven, and the edges are considerably rounded. In appearance the crystal resembles kaolinized orthoclase, though its high density (3.05) compared with that of feldspar is noted at once. A closer inspection of the crystal form likewise shows a difference from that of feldspar. The color is grayish white; on the two larger crystals it is reddish in places. Two cleavages are readily identified; the one better developed is parallel to the base $c\{001\}$, and the other one is parallel to the orthopinacoid $a\{100\}$. Cleavage planes were not present, but their orientation could readily be definitely determined by the direction of their traces. These were well developed as parallel lines on the faces of $h\{\bar{1}01\}$, $e\{0\bar{2}1\}$ and $z\{1\bar{2}0\}$.

The angular values of the crystal could be only approximately obtained with the contact goniometer. These measurements, by

which the crystal was correctly oriented, are given in the following table. Various other orientations were temporarily chosen, but only with the one adopted were the measured angles of fremontite in accord with those of amblygonite. The angular constants of amblygonite are taken for those of fremontite, pending the measurement of better crystals which would yield more accurate values. These constants are $a : b : c = 0.7334 : 1 : 0.7633$; $\alpha = 108°31$, $\beta = 97°48'$; $\gamma = 106°27'$.

Measured and calculated angles for fremontite.

	Measured.	Calculated.	
	°	°	′
$c : a = (001) : (100)$	76	75	30
$a : h = (100) : (\bar{1}01)$	51	51	16
$h : e = (101) : (0\bar{2}1)$	69	67	51
$e : z = (0\bar{2}1) : (1\bar{2}0)$	44	45	53
$z : h = (1\bar{2}0) : (\bar{1}01)$	68	66	16
$a : b = (100) : (010)$	68	69	36
$c : b = (001) : (010)$	68	67	38
$b : e = (010) : (0\bar{2}1)$	37–40	37	42
$b : z = (010) : (1\bar{2}0)$	39	38	17

A comparison of the forms observed on the two minerals is as follows:

Amblygonite.	Fremontite.
$c\{001\}$	$c\{001\}$
.....	$b\{010\}$
$a\{100\}$	$a\{100\}$
$m\{110\}$	.....
$m\{110\}$	.....
$z\{120$	$\{1\bar{2}0\}$
$e\{021\}$	$e\{021\}$
$l\{101\}$	.....
$h\{101\}$	$h\{101\}$

THE CHEMICAL COMPOSITION OF NEPHELITE.

The chemical composition of nephelite has long been a much discussed problem among mineralogists. One general theory endeavors to harmonize the analytical figures with the calculated values by the assumption of a number of complex formulas. The very complexity of these formulas is sufficient to cast doubt on their correctness. Another view is that the groups SiO_4 and Si_3O_8 can replace each other, in an isomorphous sense, so that by the presence of sufficient Si_3O_8, replacing SiO_4, the analytical figures obtained can readily be accounted for. Foote and Bradley [1] have proposed still another explanation, namely, that as a substance on crystallizing may form a "solid homogeneous solution with foreign matter," the mineral nephelite consists of a pure compound, probably $NaAlSiO_4$, with a varying amount of dissolved silica. Such an interpretation certainly is suggestive, but before it can be accepted for nephelite it must be proved that the compound $NaAlSiO_4$ can dissolve silica. Furthermore, the fact that chemically the "dissolved silica" acts in an entirely different way from any known modification of silica must be satisfactorily accounted for.

The composition of nephelite can be readily explained without assuming complex formulas and without calling on the hypothesis of "dissolved silica." The mineral albite has the formula $AlNaSi_3O_8$, and the corresponding isomorphous mineral anorthite has the formula $AlCa_{\frac{1}{2}}SiO_4$. The soda anorthite, $AlNaSiO_4$, has been prepared artificially, and Washington and Wright [2] have assumed its presence to the extent of 5.58 per cent in a feldspar (anemousite) consisting essentially of albite and anorthite in isomorphous mixture.

In the feldspars just named there are two types of compounds—$AlR'SiO_4$ and $AlR'Si_3O_8$—and their isomorphous relation, as earlier developed by Clarke,[3] led to a simple interpretation of the composition of nephelite. These compounds occur in several modifications, which are isomorphous. This relation can be best shown schematically.

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[1] Foote, H. W., and Bradley, W. M., On solid solution in minerals, with special reference to nephelite: Am. Jour. Sci., 4th ser., vol. 31, p. 25, 1911.

[2] Washington, H. S., and Wright, F. E., A feldspar from Linosa and the existence of soda anorthite (carnegieite): Am. Jour. Sci., 4th ser., vol. 29, p. 52, 1910.

[3] Clarke, F. W., The constitution of the silicates: U. S. Geol. Survey Bull. 125, 1895.

Modifications of compounds $AlR'SiO_4$ and $AlR'Si_3O_8$.

Compound.	Hexagonal.	Monoclinic.	Triclinic.
$AlNaSiO_4$	Essential component of nephelite; artificially prepared.	.....	Artificially prepared; naturally only in mixture (carnegieite).
$AlKSiO_4$	Kaliophilite		
$AlCa_{\frac{1}{2}}SiO_4$	Present in small amounts in the calcic varieties of nephelite.	Celsian is the corresponding barium salt.	Anorthite.
$AlNaSi_3O_8$	Naturally only in mixture in nephelite.	Barbierite	Albite.
$AlKSi_3O_8$	.....	Orthoclase	Microcline.
$AlCa_{\frac{1}{2}}Si_3O_8$			

The mineral nephelite is then an isomorphous mixture of the compounds crystallizing in the hexagonal modification, which are $AlNaSiO_4$ (essential component), $AlKSiO_4$ (kaliophilite), and $AlNaSi_3O_8$ (best known in its triclinic form as albite).

To show that the explanation offered is in agreement with the analyses of nephelite it will suffice to quote two analyses, one by Foote and Bradley and one by Morozewicz (No. V in paper of Foote and Bradley). These have been chosen for the reason that they are among the best analyses and show a minimum amount of other bases, such as CaO and Fe_2O_3.

The nephelite analyzed by Foote and Bradley consists, as calculated from their ratios, of the following compounds in the proportions indicated: 60 parts or 19.0 per cent of $KAlSiO_4$, 245 parts or 70.4 per cent of $NaAlSiO_4$, and 21 parts or 10.6 per cent of $NaAlSi_3O_8$. The comparison of the analysis with the figures calculated from this composition is very close, as is shown below.

Comparison of analysis of nephelite by Foote and Bradley with calculated values.

	Analysis.	Calculated.
SiO_2	44.46	44.45
Al_2O_3	33.11	33.37
Fe_2O_3	.96	
K_2O	5.61	5.66
Na_2O	16.32	16.52
H_2O	.38	.....
	100.84	100.00

The analysis made by Morozewicz yields the following composition: 62 parts or 19.7 per cent of $KAlSiO_4$, 259 parts or 74.7 per cent of $NaAlSiO_4$, and 11 parts or 5.6 per cent of $NaAlSi_3O_8$. As in the other case, the comparison of the analysis with the values calculated from this composition shows a very close agreement.

Comparison of analysis of nephelite by Morozewicz with calculated values.

	Analysis.	Calculated.
SiO_2	42.71	43.04
TiO_2	.04	.....
Al_2O_3	33.83	34.20
Fe_2O_3	.40	
K_2O	5.86	5.89
CaO	.32	16.87
Na_2O	16.46	
H_2O	.18	.....
Impurities	.06	.....
	99.86	100.00

The figures prove that the composition of the mineral nephelite is best explained by assuming an isomorphous relation of SiO_4 and Si_3O_8.

The remarkable fact that the compound $KAlSiO_4$ is always present in nephelite to the extent of about 20 per cent has not yet received any adequate explanation.

LARGE CRYSTALS OF BLOEDITE.

Some bloedite recently found by Mr. Hoyt S. Gale, of the Geological Survey, is remarkable for the large size of the crystals. An extensive deposit of soda forms a crust on Soda Lake, in Carrizo Plain, San Luis Obispo County, Cal. This deposit has been described by Arnold and Johnson,[1] who give a detailed analysis of the saline crust that shows it to be nearly pure sodium sulphate with 1.66 per cent of MgO. In the black mud below this crust were found the isolated crystals of bloedite, a hydrous magnesium sodium sulphate with 12 per cent of MgO.

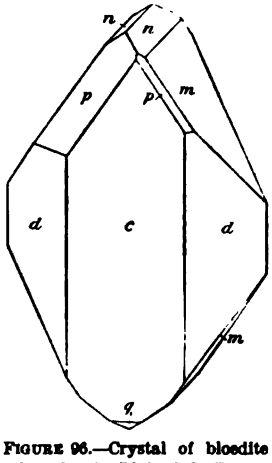


FIGURE 96.—Crystal of bloedite from Carrizo Plain, Cal. Forms: $c\{001\}$, $d\{011\}$, $m\{110\}$, $n\{210\}$, $q\{\bar{2}01\}$, $p\{111\}$. The crystal is drawn with the base $c\{001\}$ vertical.

The larger crystals have a dark, almost black appearance when the superficial covering of gray mud is removed, though the smaller crystals are nearly colorless, the black appearance being due to impurities. In places the larger crystals are likewise nearly colorless and translucent and in small pieces transparent. The clear and glassy fragments which do not show any cleavage greatly resemble quartz fragments.

The largest crystal at present on hand measures 16.5 by 10.5 by 3.5 centimeters and weighs 652 grams. The crystals are flattened somewhat parallel to the base and show the following forms:

Large: $c\{001\}$, $d\{011\}$, $m\{110\}$.
Medium: $n\{210\}$, $p\{111\}$.
Small: $q\{\bar{2}01\}$, $s\{\bar{2}11\}$, $u\{\bar{1}11\}$, $x\{\bar{1}21\}$.

The measurements were made with a contact goniometer and gave the following results:

[1] Arnold, Ralph, and Johnson, H. R., Sodium sulphate in Soda Lake, Carrizo Plain, San Luis Obispo County, Cal.: U. S. Geol. Survey Bull. 380, pp. 369-371, 1909.

Measurements of bloedite crystals.

Form.	Measured.	Calculated.	
	°	°	′
$m(110) : p(111)$	47	46	42
$c(011) : q(\bar{2}01)$	50	50	06
$c(001) : p(111)$	36	36	55
$n(210) : n'''(2\bar{1}0)$	68	67	06
$m(110) : m'''(1\bar{1}0)$	105	105	58
$d(011) : d(0\bar{1}1)$	67	66	46
$c(001) : s(\bar{2}11)$	55	55	16½
$c(001) : u(\bar{1}11)$	43	42	05

The form $x(\bar{1}21)$ was determined by zonal relations.

A peculiarity noted on almost all the crystals examined is that the pair of faces of the pyramid $p\{111\}$ are very unequally developed, as shown in figure 96. In order to show better the relative development of the faces, the drawing was made with the a and c axes interchanged, so that the basal pinacoid $c\{001\}$ is shown in vertical position.

The analysis made on selected pure material gave the following values:

Analysis of bloedite from California.

H_2O	21.37
MgO	11.93
Na_2O	18.26
SO_3	48.11
	99.67

These values are close to those that are required by the formula $Na_2Mg(SO_4)_2.4H_2O$.

ALUNITE FROM MARYSVALE, UTAH.

The occurrence of alunite near Marysvale, Utah, has been fully described by Butler and Gale.[1] On some of the more coarsely crystalline alunite small cavities were noted in which were found crystals showing the base $c\{0001\}$ and the rhombohedron $r\{10\bar{1}1\}$, both developed as large faces whose edges were in part truncated by narrow faces of $s\{02\bar{2}1\}$.

An analysis of a selected clear-pink, translucent, coarsely granular crystalline specimen gave the results shown below in column 1, whereas an analysis of the very compact fine-granular alunite rock (column 2), which has a decided porcelain-like appearance, showed that it was much impurer than the better-crystallized granular material.

Analyses of alunite from Marysvale, Utah.

	1. Coarse granular variety.	2. Compact fine-grained rock.	Calculated composition.
Al_2O_3	37.18	34.40	36.97
Fe_2O_3	Trace.	Trace.	.....
K_2O	10.46	9.71	11.36
Na_2O	.33	.56	.....
SO_3	38.34	36.54	38.63
P_2O_5	.58	.50	.....
H_2O-	.09	.11	.....
H_2O+	12.90	13.08	13.04
SiO_2	.22	5.28	.....
	100.10	100.18	100.00

The first analysis, made on pure material, agrees well with the composition of the mineral as calculated from the formula $3Al_2O_3.K_2O.4SO_3.6H_2O$.

Laboratory experiments showed that the powdered mineral, when ignited, gives off all its water and three-quarters of its sulphuric acid. The remaining quarter is combined with the potassium as potassium sulphate and may be dissolved out with water. The residue consists of aluminum oxide plus the impurities, such as silica, which were present in the sample. The maximum amount of alumina found in the water leach of several experiments was 0.25 per cent. It is prob-

[1] Butler, B. S., and Gale, H. S., Alunite, a newly discovered deposit near Marysville, Utah: U. S. Geol. Survey Bull. 511, 1912.

able that a small amount of potassium sulphate was volatilized by the heat. The following results were obtained by igniting the powdered alunite and subsequent leaching with water:

	Per cent.
Volatilized (H_2O, 13; SO_3, 29; K_2SO_4(?), 2)	44
Insoluble residue (Al_2O_3)	37
Water-soluble residue (K_2SO_4)	18
	99

It follows that about 92 per cent of the total potassium sulphate in the mineral was obtained in a water-soluble form by this treatment. A higher percentage can doubtless be obtained by regulating the heat, as it is believed that in the experiments some of the potassium sulphate was volatilized.

According to these experiments about 32 per cent of the ignited alunite consists of available potassium sulphate which can be extracted and recovered by simple water leaching and evaporation. The remaining 68 per cent consists of alumina (Al_2O_3) plus the impurities of the mineral sample.

THE COMPOSITION AND RELATIONS OF CUSTERITE.

OCCURRENCE AND ASSOCIATION.

Custerite has been described by Umpleby[1] as occurring in a contact zone of granite porphyry with Mississippian limestone, 3½ miles southwest of Mackay, Custer County, Idaho. The zone is worked for copper, and the ore minerals, principally chalcopyrite and its oxidation products, are intimately associated with garnet, diopside, magnetite, fluorite, and other contact minerals in bodies that are nearly coincident in extent with original limestone inclusions. In some of these inclusions none of the original limestone remains, though locally its bedded structure is preserved in the garnet-diopside rock, but in others a core of unaltered blue limestone grades outward through pale-blue, partly recrystallized limestone into white marble and on into a zone made up principally of garnet, diopside, and magnetite. The custerite was collected between the garnet-diopside and marble zones which fringe one of these inclusions.

PHYSICAL AND OPTICAL PROPERTIES.

The results of microscopic study indicate that custerite is monoclinic. Two cleavages were noted, one parallel to the base and the other parallel to a prism. The hardness is 5 to 6, the density 2.91. The crystals show lamellar twinning like albite. As determined by Umpleby and Larsen, the refractive indices are, for sodium light, $\alpha=1.586\pm0.005$, $\beta=1.589\pm0.005$, $\gamma=1.598\pm0.005$.

Fuller description of the optical relation is given in the paper cited, in which the microscopic characterization of custerite is summarized as follows:

> Custerite is characterized microscopically by its moderate index of refraction, low birefringence, polysynthetic twinning, maximum extinction angle of twin lamellæ of 6°–7°, positive optical character, distinct dispersion of the optic axes with $\rho<\nu$, and three cleavages which intersect at high angles. There is no known mineral species from which it may not be readily distinguished optically. Its birefringence and twinning suggest albite, but its refringence is much higher. Its relief, lack of color, and cleavage in thin section might at first glance lead to its being mistaken for a colorless pyroxene, but its refringence and birefringence are lower, and its extinction angle is less than in all pyroxenes except ægirite. It resembles hillebrandite in index of refraction and birefringence, but that mineral is orthorhombic, optically negative, and occurs in fibrous forms. In relief and birefringence also it resembles eudialyte, which, however, is uniaxial and occurs in association with soda minerals.

[1] Umpleby, J. B., Schaller, W. T., and Larsen, E. S., Custerite, a new contact-metamorphic mineral: Am. Jour. Sci., 4th ser., vol. 36, p. 385, 1913.

It is believed that custerite is a mineral of rare occurrence, for its optical properties are so distinctive that it would scarcely have been overlooked. In the hand specimen, however, it is so unpromising in appearance that thin sections of it may never have been cut. The mineral should be looked for in fluorine-bearing contact zones, apparently in the border phases of the metamorphism.

CHEMICAL PROPERTIES.

PYROGNOSTICS.

When heated gently in a closed tube, custerite turns a transitory yellow and phosphoresces with a golden-yellow light. As seen in a darkened room, the color of the glow is like that of a deep-colored golden beryl. On increasing the heat the phosphorescence is destroyed and water is given off. The mineral does not decrepitate. A white ring, due to the fluorine, is obtained by heating the mineral at a temperature sufficient to melt the glass tube. In the blowpipe flame custerite fuses with difficulty to an opaque white enamel.

The mineral is very readily decomposed by acids, gelatinous silica separating so quickly when the powdered mineral is treated with HCl as to form a stiff coherent mass. The separated gelatinous silica floats around in an excess of acid, the solution itself not gelatinizing on further boiling. Custerite therefore does not "gelatinize" like natrolite.

QUANTITATIVE COMPOSITION.

The chemical analysis showed that water, fluorine, silica, and lime were the essential constituents, the small amounts of iron and magnesium present being probably due to magnetite and diopside, respectively. Fairly pure, fresh material, suitable for analysis, was available only in portions of 0.25 to 0.75 gram.

The analytical results obtained are shown in the following table:

Analyses and ratios of custerite.

	1	2	Average.	Ratios.
SiO_2	32.13	32.20	32.17	0.536
CaO	55.11	.....	55.11	.984
H_2O	5.53	5.06	5.30	.294
F	8.12	.....	8.12	.427
MgO	1.19	1.19	1.19	.030
Magnetite	.85	1.14	1.00	.....
			102.89	
			$O=F_2-3.42$	
			99.47	

These results were verified by a partial analysis (water not being determined) of a different, somewhat less pure portion of the same

specimen of custerite. The results obtained are: SiO_2, 33.46; CaO, 53.93; F, 7.29; MgO, 1.41; magnetite, 2.13. Alkalies were not determined on any of the samples because of paucity of material. Some of the whiter, chalky-looking material gave less water than the fresh material, several different samples yielding from 2 to 3 per cent H_2O instead of the 5 or 6 per cent given in the above analyses. Whether this represents an alteration of the custerite or a much impurer sample could not be determined on the scanty material available.

INTERPRETATION OF ANALYSIS.

The ratios derived from the above analytical figures can be interpreted by considering either that the small amount of magnesia belongs to the custerite or that it represents admixed diopside. These alternatives are shown in the table below.

Interpretation of ratios of custerite analysis.

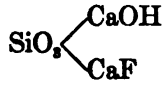
	Ratios.	Combining CaO+MgO.	Deducting diopside.	Combining water and fluorine.
SiO_2	0.536	2.00	2.00	2.00
CaO	.984	3.78	4.01	4.01
MgO	.030		.....	.....
H_2O	.294	1.10	1.24	2.14 H_2O or 4.27 F
F	.427	1.59	1.79	

The formula derived for custerite is Ca_2SiHFO_4, with some of the fluorine replaced by water (hydroxyl). The composition may also be expressed as a mixture of the two compounds $2SiO_2.4CaO.2H_2O$ and $2SiO_2.4CaO.4F$, with the first one slightly in excess. The relation of the fluorine to water (hydroxyl) can be much better shown in the empirical formula, according to which the ratios reduce to $Ca_4Si_2O_6(OH,F)_4$ with the ratio of hydroxyl (OH) to fluorine (F) as 2.48 : 1.79, or nearly 4 : 3.

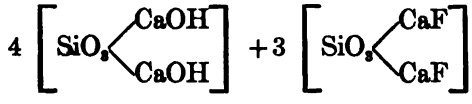
No water was given off when custerite was heated to 110°, indicating that the water is an inherent part of the mineral. The temperature at which the water does go off was not determined, but the observation was repeatedly made that the phosphorescence phenomenon displayed itself and was destroyed by heat before the water was given off. Some powdered custerite, placed in a watch glass with several cubic centimeters of water, immediately gives a deep-red color with a few drops of phenolphthalein. This reaction was described by Clarke,[1] who has suggested that it is indicative of the presence of the univalent group CaOH. As the ratio of OH to F is

[1] Clarke, F. W., The alkaline reaction of some natural silicates: U. S. Geol. Survey Bull. 167, p. 156, 1900.

approximately 1 : 1, the formula of custerite may be structurally interpreted as a metasilicate, as follows:



The ratio of hydroxyl (OH) to fluorine (F) being not exactly 1 : 1 but more nearly 4 : 3, custerite may be more accurately considered as an isomorphous mixture of the following compounds, in the ratio indicated.



RELATION TO OTHER MINERALS.

There are only three minerals known to which custerite is related in composition. These are zeophyllite, cuspidine, and hillebrandite. The relation in composition can be best shown by directly comparing their analyses:

Comparison of composition of custerite with that of related minerals.

	Custerite.	Zeophyllite.	Cuspidine.		Hillebrandite.
			Franklin Furnace.	Vesuvius.	
SiO_2	32.17	38.84	32.36	32.80	32.59
CaO	55.11	44.32	61.37	61.12	57.76
H_2O	5.30	8.98	.....	.....	9.36
F	8.12	8.23	9.05	9.88	.....
Rest	2.19	2.62	1.46	.42	.53
	102.89	102.99	104.24	104.22	100.24
Deduct $O=F_2$	−3.42	−3.47	−3.81	−3.98	
	99.47	99.52	100.43	100.24	

Zeophyllite is the only one of the three minerals which contains both water and fluorine. The proportions of silica and lime are different from those in custerite, though structurally its formula may be written in a somewhat similar way. The mineral is described as rhombohedral, the crystals being composed of a uniaxial center surrounded by a biaxial border. On being heated the mineral becomes uniformly and permanently uniaxial. In crystal form and physical and optical properties there is no relation between zeophyllite and the other minerals chemically related to custerite. In its paragenesis zeophyllite is also totally different from custerite,

being a zeolite-like mineral found in basalt with natrolite, calcite, apophyllite, analcite, etc. A specimen of zeophyllite obtained through the kindness of Dr. Koechlin, of the Vienna Hof-Museum, was tested for its alkaline reaction and found to give only a very faint pink color with phenolphthalein.

The dual optical character of zeophyllite suggests strongly that it is polymorphous. Possibly the uniaxial compound is the zeolite-like mineral, bearing no relation to custerite, cuspidine, or hillebrandite. The biaxial compound, not found as such in nature, may possibly represent a compound similar in properties to custerite, cuspidine, and hillebrandite. Its formula, $Ca_4Si_3H_4F_2O_{11}$, can be written as that of custerite plus one part of metasilicic acid, thus: $Ca_4Si_2H_2F_2O_8$ (custerite) + H_2SiO_3, but what significance, if any, is to be attached to this fact is not known. The formula of zeophyllite can be interpreted structurally in a way analogous to that of custerite:

$$\begin{array}{l} CaF-SiO_3 \diagdown \\ \qquad\qquad\quad Ca \\ \qquad\quad SiO_3 \diagup \qquad + 2H_2O \\ \qquad\qquad\quad Ca \\ CaF-SiO_3 \diagup \end{array}$$

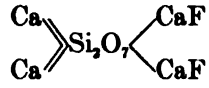
which would explain the fact that zeophyllite does not give a strong alkaline reaction with phenolphthalein but which seems inconsistent with the fact that less than 1 per cent of the water is given off at 110°. Other structural interpretations are of course possible.

Cuspidine, found originally at Vesuvius, has recently been noted at Franklin Furnace, N. J., by Palache. At Vesuvius it was found as well-developed crystals in druses associated with augite, hornblende, biotite, garnet, sarcolite, haüyne, and calcite (derived from altered cuspidine). Granular aggregates resembling a fine-grained diabase, composed of cuspidine with augite and biotite, were also noted. Attention may also be called to the "cuspidine-like mineral"[1] found with green magnesia mica and white sodalite and occurring in rhombic prisms, apparently different from cuspidine. The composition of this material is not known, though Zambonini[2] considers it identical with humite.

The density of the Franklin Furnace cuspidine is given as 2.965–2.989, and that of the Vesuvius cuspidine, as determined by Zambonini, as 2.962; the average being 2.97. The formula derived by Zambonini, $Ca_2(CaF)_2Si_2O_7$, is in perfect accord with his own analysis and with Warren's analysis of the Franklin Furnace material. The presence of only 0.57 per cent of water (not determined according

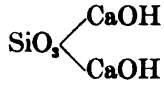
[1] Rath, G. von, Zeitschr. Kryst. Min., vol. 8, p. 45, 1884.
[2] Zambonini, F., Appendice alla Mineralogia Vesuviana: Accad. Sci. Napoli Atti, vol. 12, p. 44, 1912.

to Warren's analysis) would suffice to bring the ratio of $[F+(OH)]$: SiO_2 to 1.00 : 1.00 instead of 1.00 : 0.88, as calculated from his analysis. Structurally the formula of cuspidine can be interpreted as



which does not show any direct relation to that of custerite.

Hillebrandite is genetically similar to custerite, being one of the products of contact metamorphism of limestone. A sample of hillebrandite kindly furnished for study by Dr. F. E. Wright yielded 0.77 per cent of water at 110° and 9.64 per cent on ignition (calculated 9.45 per cent). The strong alkaline reaction with phenolphthalein as described by Wright was confirmed and suggests the presence of the CaOH group. From these results the composition of hillebrandite can be readily interpreted as a metasilicate with the following structural formula:



This formula is identical in type with that of custerite and suggests at once that custerite is an isomorphous mixture of hillebrandite and a theoretic fluo-hillebrandite, in which all the hydroxyl is replaced by fluorine. This conception is simple and rational but is opposed by other considerations.

As cuspidine has been found at two widely separated localities, the inference may be justified that in the presence of much fluorine and little or no water a mineral of the cuspidine formula, $3CaO.2SiO_2CaF_2$, would always form instead of a fluo-hillebrandite with the formula $2CaO.2SiO_2.2CaF_2$. In other words, fluo-hillebrandite seems to be unstable under the metamorphic conditions prevailing, though this inference rests solely on the fact that at the only two localities where a calcium fluo-silicate occurs a compound of different type (cuspidine) was formed. It seems likely, therefore, that, in view of the isomorphous replacement of fluorine and hydroxyl, the isomorphous series of which hillebrandite is the hydroxyl end consists of the two end members $(CaOH)_2SiO_3$ and $(CaF)(CaOH)SiO_3$ and not of the theoretic end members $(CaOH)_2SiO_3$ and $(CaF)_2SiO_3$.

The symmetry of hillebrandite and custerite is apparently different, though some of the properties of hillebrandite could not be as definitely determined as those of custerite. Hillebrandite is fibrous and orthorhombic, whereas custerite is granular and monoclinic, with a close approach to orthorhombic symmetry, as is indicated by the nearly rectangular cleavages and low extinction angle. The custerite and hillebrandite compounds may both be dimorphous, only the two

nonisomorphous end members of the four possible compounds being known.

The status of the relations of these minerals, so far as can be judged by the available evidence, seems to be somewhat as is given below.

Cuspidine: $Ca_4Si_2F_2O_7$.

Theoretic fluo-hillebrandite: $Ca_4Si_2F_4O_6$. Unstable, nonexistent.

Custerite: $Ca_4Si_2F_2(OH)_2O_6$. Dimorphous; orthorhombic form isomorphous with hillebrandite (not known) and monoclinic.

Hillebrandite: $Ca_4Si_2(OH)_4O_6$. Dimorphous; monoclinic form isomorphous with custerite (not known) and orthorhombic.

Zeophyllite: $Ca_4Si_3H_4F_2O_{11}$. Dimorphous; the known form not related to the above-named minerals.

The close chemical relation of these four minerals can be shown by writing their formulas so as to keep intact the common compound, $Ca_4Si_2F_2O_7$.

Cuspidine.....$Ca_4Si_2F_2O_7$.
Custerite.....$Ca_4Si_2F_2O_7.H_2O$ (or cuspidine plus water).
Hillebrandite. $Ca_4Si_2(OH)_2O_7.H_2O$.
Zeophyllite....$Ca_4Si_2F_2O_7.H_2O.SiO_2$ (or cuspidine plus water and silica).

These relations suggest the existence of a hydroxy-cuspidine, $Ca_4Si_2(OH)_2O_7$, and the derivability of custerite and zeophyllite (or a polymorphic form of the zeophyllite compound) from cuspidine by the actual addition of water and silica.

The essential properties of the four minerals considered in the preceding paragraphs are briefly tabulated below for future reference.

Properties of custerite and related minerals.

	Custerite.	Zeophyllite.	Cuspidine.	Hillebrandite.
Composition	$Ca_4Si_2H_2F_2O_8$	$Ca_4Si_3H_4F_2O_{11}$	$Ca_4Si_2F_2O_7$	$Ca_4Si_2H_4O_{10}$.
Symmetry	Monoclinic	Rhombohedral	Monoclinic	Orthorhombic.
Cleavage	Two, basal and prismatic.	One, basal	One, basal	Prismatic (?).
Hardness	5–6	3	5–6	5–6.
Density	2.96	2.75	2.97	2.69.
Fusibility	Difficult	Very easy	Difficult	Difficult.
Axial plane	Normal to basal cleavage.	Normal to cleavage.	{010}, normal to cleavage.	Parallel to cleavage.
Index γ	1.598	1.565	1.602[a]	1.612.
Index β	1.589	.....	1.595[a]	
Index α	1.586	1.560	1.590[a]	1.605.
Birefringence	0.011	0.005	0.012[a]	0.007.
2E	105°	0–27½°	110°	60–80°.
Dispersion	Strong, $\rho > v$	$\rho < v$	Crossed, very distinct, $\rho > v$.	$\rho < v$.
Sign	Positive	Negative	Positive[a]	Negative.
Extinction	6½°	.....	5°	0°.
Twinning	Prominent, polysynthetic.	.....	Twinning plane (100).	
Elongation	.....	.....	.....	Z.

[a] Data kindly furnished by Esper S. Larsen, measured on the Vesuvius mineral.

THE COMPOSITION OF HODGKINSONITE.

OCCURRENCE AND ASSOCIATIONS.

The occurrence of hodgkinsonite at Franklin Furnace, N. J., is described by Palache[1] as follows:

> Hodgkinsonite is a hydrous silicate of zinc and manganese crystallizing in the monoclinic system. It occurs in seams in massive granular ore of the typical willemite-franklinite mixture; the seams are generally very thin with but a film of the mineral which is always associated with white barite and not uncommonly with plates of native copper. Locally the film thickens to a narrow vein, and then the new mineral may show individuals up to 2 centimeters across, sharply angular in form and apparently with crystal faces but in reality determined in their outline wholly by the older platy barite which incloses them. The clear pink color and brilliant cleavage of hodgkinsonite together with the snow-white barite make such specimens both striking and attractive in appearance.

The crystals so far obtained have occupied cavities in the thicker veins and show evidence of solution, the faces being generally faceted and dull. The largest crystal seen measures about 1 centimeter in length. In the cavities hodgkinsonite is accompanied by black rhombohedral crystals of pyrochroite and scalenohedral crystals of calcite, both later in age and partly incrusting it. The hodgkinsonite crystals are implanted directly on willemite or franklinite, and in one specimen on manganese garnet. The association and mode of occurrence both indicate a pneumatolytic origin for the new mineral.

CRYSTALLOGRAPHY.

Hodgkinsonite was determined by Palache to be monoclinic with normal symmetry. The highly perfect cleavage, normal to the symmetry plane, has been taken as the basal pinacoid. In other directions the fracture is conchoidal. The habit of the crystals is acute pyramidal. The axial ratio[2] is $a:b:c=1.538:1:1.1075$, $\beta=84°\ 35'$. The forms determined are $c\{001\}$, $m\{110\}$, $l\{210\}$, $s\{011\}$, $o\{021\}$, $v\{\bar{4}03\}$, $w\{\bar{2}01\}$, $t\{\bar{4}01\}$, $p\{111\}$, $r\{221\}$, $n\{\bar{3}11\}$.

CHEMICAL PROPERTIES.

PYROGNOSTICS.

The mineral decrepitates when held in the blowpipe flame, wherein it fuses readily and quietly to a brown enamel. When heated in a closed tube it decrepitates strongly, splitting up into numerous thin

[1] Palache, Charles, and Schaller, W. T., Hodgkinsonite, a new mineral from Franklin Furnace, N. J.: Washington Acad. Sci. Jour., vol. 3, p. 474, 1913.

[2] Palache, Charles, Supplementary note on the crystal form of hodgkinsonite: Washington Acad. Sci. Jour., vol. 4, p. 154, 1914.

cleavage scales which on further heating yield water and become brown in color. The mineral is readily soluble in acid, yielding gelatinous silica.

QUANTITATIVE COMPOSITION.

The chemical analyses of hodgkinsonite were made on carefully selected cleavage fragments of a clear pink color and gave the following results. Quarter-gram samples were used, as the total amount of available material was only somewhat over a gram.

Analyses and ratios of hodgkinsonite.

	1	2	3	Average.	Ratios.	
SiO_2	19.92	19.89	19.77	19.86	0.331	1.02
MnO	20.39	20.97	.....	20.68	.291	2.98
ZnO	52.93	(a)	.....	52.93	.653	
CaO	.99	.88	.....	.93	.017	
MgO	.04	.....	.....	.04	.001	
H_2O	.....	.....	b 5.77	5.77	.321	.99
					100.21	

a A duplicate determination of ZnO, of which a small amount was lost, gave 51.38 per cent.
b Determined directly by fusing the mineral with sodium carbonate and collecting the water in a calcium chloride tube. A determination of the loss on ignition, corrected for oxidation of the manganese, gave 4.68 per cent.

A doubtful trace of lead was encountered, but iron and chlorine were absent. No water was given off by the mineral at 110°.

The ratios yield the formula $3RO.SiO_2.H_2O$, in which R is chiefly zinc and manganese. If the manganese, calcium, and magnesium are arbitrarily taken together, then the ratio of $MnO+CaO+MgO$ to ZnO is 309 to 653, or 1 : 2.11, or nearly 1 : 2. The formula may then be written $MnO.2ZnO.SiO_2.H_2O$, which may, as the water is all constitutional, be interpreted as $Mn.(ZnOH)_2.SiO_4$.

CRYSTALS OF PISANITE FROM DUCKTOWN, TENNESSEE.

Some specimens of pisanite from Ducktown, Tenn., were sent to the writer for crystallographic study by Prof. F. R. Van Horn, of Cleveland, Ohio, who has recently[1] given a full description of the occurrence and composition of the mineral. Several crystals were detached from the specimens and measured with the following result:

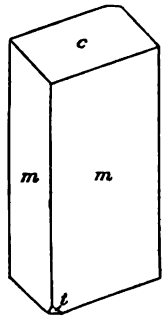


FIGURE 97.

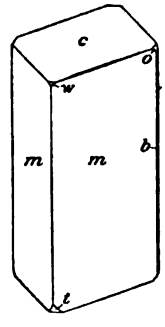


FIGURE 98.

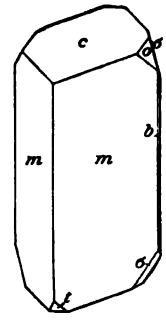


FIGURE 99.

FIGURE 97.—Crystal 1, pisanite from Ducktown, Tenn. Forms: $m\{110\}$, $c\{001\}$, $t\{\bar{1}01\}$.

FIGURE 98.—Crystal 2, pisanite from Ducktown, Tenn. Forms: $b\{010\}$, $m\{110\}$, $c\{001\}$, $o\{011\}$, $w\{103\}$, $t\{\bar{1}01\}$.

FIGURE 99.—Crystal 3, pisanite from Ducktown, Tenn. Forms: $b\{010\}$, $m\{110\}$, $c\{001\}$, $o\{011\}$, $t\{\bar{1}01\}$, $\sigma\{\bar{1}21\}$.

Forms determined:

$b\{010\}$, very narrow, figures 98 and 99.
$c\{001\}$, large, figures 97, 98, 99. Cleavage.
$m\{110\}$, large, dominant form, figures 97, 98, 99.
$o\{011\}$, small, figures 98 and 99.
$w\{103\}$, minute, figure 98.
$t\{\bar{1}01\}$, minute but larger than w, figures 97, 98, 99.
$\sigma\{\bar{1}21\}$, minute, figure 99.

Average measured and calculated angles of pisanite from Ducktown, Tenn.

	Measured.				Calculated.			
	ϕ		ρ		ϕ		ρ	
	°	′	°	′	°	′	°	′
$b\{010\}$	0	17	90	00	0	00	90	00
$c\{001\}$	89	23	15	54	90	00	15	11
$m\{110\}$	41	34	90	00	41	36	90	00
$o\{011\}$	9	35	57	19	10	07	57	04
$w\{103\}$	88	27	36	29	90	00	35	48
$t\{\bar{1}01\}$	89	21	47	06	90	00	47	09
$\sigma\{\bar{1}21\}$	18	33	72	06	19	32	72	46

[1] Van Horn, F. R., Notes on a new occurrence of pisanite and arsenopyrite, and some large staurolite crystals from the Ducktown district, Tenn.: Am. Jour. Sci., 4th ser., vol. 37, p. 40, 1914.

THE REFRACTIVE INDICES OF STRENGITE.

The only published figures for the refractive indices of strengite, $Fe_2O_3.P_2O_5.4H_2O$, which could be found are those given by Schroeder van der Kolk.[1] His figures are $1.81+0.03$, which can be stated, as Lacroix[2] did, in the form $\alpha=1.81$, $\gamma=1.84$. Determination of these values for a manganese strengite from California gave $\alpha=1.70$–1.71, $\gamma=1.72$–1.73. Lacroix[3] determined the mean index of similar material (which he called angelardite) as approximately 1.70. It therefore seemed necessary to redetermine the refractive indices of typical strengite in order to bring the conflicting determinations in accord.

Professor Ledroit, of Mainz, very kindly presented several specimens of the mineral from the Eleonore mine, on the Dunsberg, near Giessen. The strengite forms small spherulites associated with beraunite (eleonorite), cacoxenite, etc. Crushed fragments of these spherulites were used for determining the minimum and maximum refractive indices. The oil-immersion method was used, and the results obtained are as follows:

α (normal elongation of fibers)$=1.71$.
γ (parallel elongation of fibers)$=1.735$.
$\gamma-\alpha=0.025$.

The figures given by Schroeder van der Kolk are therefore wrong, and it seems most probable that his figure 1.81 was miscopied for 1.71.

[1] Tabellen zur mikroskopischen Bestimmung der Mineralien, p. 54, 1906.
[2] Lacroix, A., Minéralogie de la France, vol. 4, p. 475, 1910.
[3] Idem, p. 523.

THE CALCULATION OF A MINERAL FORMULA.

In the calculation of the ratios of a mineral analysis, it is customary to select arbitrarily one of the constituents as unity or some multiple of unity and on this basis to calculate the ratios of the other constituents. As an example the analysis of pearceite from the Veta Rica mine, Sierra Mojada, Coahuila, Mexico, as recently given [1] by Van Horn and Cook, is reproduced below.

Analysis and ratios of pearceite.

	Analysis.	Ratios.		
S	17.46	0.5444	10.80	11
As	7.56	.1008	2.00	2
Ag	59.22	[a] .2744	7.886	8
Cu	15.65	[b] .1231		
Sb	.00			
	99.89			

[a] Considered as Ag_2. [b] Considered as Cu_2.

The ratios are sufficiently close to 11 : 2 : 8 to show that these are the correct values. The true ratios are very much closer to 11 : 2 : 8 than those given by Van Horn and Cook, as will be shown below.

The first column from the ratios given above is reproduced below (1) with the figures for silver and copper combined, and all the figures multiplied by 100 for convenience. By taking the lowest number as unity it is readily seen that the approximate ratio is $5\frac{1}{2} : 1 : 4$. On dividing the first value by 2 times $5\frac{1}{2}$ (these numbers are doubled to avoid fractions) the second by 2 times 1 and the third by 2 times 4, the results under (2) are obtained. These numbers should be nearly the same. Their average is 4.986. Dividing now the ratios obtained from the analysis by this average we obtain the figures given under (3), which are much closer to 11, 2, and 8 respectively than those given by Van Horn and Cook.

	(1)	(2)	(3)
S	$54.44 \div (2 \times 5\frac{1}{2})$	$=4.949$	10.92
As	$10.08 \div (2 \times 1)$	$=5.040$	2.02
Ag_2+Cu_2	$39.75 \div (2 \times 4)$	$=4.969$	7.97
		Average $=4.986$	

[1] Van Horn, F. R., and Cook, C. W., A new occurrence of pearceite: Am. Jour. Sci., 4th ser., vol. 31, p. 518, 1911.

Ratios like those given above under (3), which vary considerably from the whole numbers they approximate, should not be compared as they stand. The figures should be reduced to multiples of approximate unity, which can then be directly compared, as the following table shows. In the last column only two decimals are expressed. If the third decimal is below 5, it is neglected. If it is 5 or above, the second decimal is increased 1.

S	$10.92 = 11 \times 0.993 = 11 \times 0.99$
As	$2.02 = 2 \times 1.01 = 2 \times 1.01$
Ag_2+Cu_2	$7.97 = 8 \times 0.996 = 8 \times 1.00$

These figures show that the ratios deduced from the pearceite analysis are in fact very close to the whole numbers 11 : 2 : 8, a fact that is not brought out by the ratios 10.80 : 2.00 : 7.886 given by Van Horn and Cook, which were obtained by arbitrarily assigning a whole number to one of the values. The form of the last set of ratios given above expresses most accurately the relations calculated from the analysis.

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